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Anterior cruciate ligament (ACL) injury affects roughly 150,000 people each year, and the majority of those affected are women and girls. Major risk factors for sustaining an ACL injury are condensed into the following categories: (1) anatomical/structural, (2) hormonal, (3) genetic, and (4) neuromechanical. Of the risk factor categories, neuromechanical is the most modifiable. Training programs, or ACL injury prevention programs (IPPs), have been implemented with the goal of modifying movement to reduce neuromechanical risk factors. However, these programs have had limited success at reducing the total number of ALC injuries in sport. One area of refinement in ACL IPPs is the adoption of newer motor learning theories that have evolved in recent years. A relatively new motor learning theory, Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) Theory, contains three key components that have shown to aid motor learning, retention, and transfer: (1) external focus of attention, (2) autonomy of support, (3) and enhanced expectancies. However, OPTIMAL Theory has primarily been studied in upper extremity tasks. To close these gaps between motor learning and ACL IPPs, this dissertation had three purposes: (1) compare performance of an OPTIMAL Theory group to a control group in the jump/landing task of basketball rebounding, (2) examine the extent to which motor performance from the basketball rebounding task transferred to a maximal effort vertical jump task (i.e., a similar dynamic task) and (3) examine the extent to which motor performance from the basketball rebounding task transferred to a standing balance task (i.e., a static task). A total of 60 young healthy adults participated in a two-day study and were randomly assigned to the OPTIMAL (n=30; 21 (3.6) years; 172.2 (10.9) cm; 81.0 (22.8) kg; M=15, F=15) or the control group (n=30; 22.1 (3.3) years; 167.9 (9.7) cm; 71.6 (16.1) kg; M=10, F=20). Day one included pre- and post-testing of five rebounds, five maximal effort vertical jumps, and standing balance testing. In between the pre- and post-tests was a practice block that included 25 rebounds, with the OPTIMAL group receiving instructions that included external focus, autonomy of support, and enhanced expectancy components, whereas the control group was only given the task goal of rebounding the ball at the highest point. After a 24-hour retention period, all participants completed retention testing of all three tasks which mimicked the pre-testing. Analyses of variance were used to examine the extent to which the OPTIMAL Theory instructions/feedback influenced knee flexion and hip-knee alignment—known ACL injury risk factors—during the rebounding and maximal effort vertical jump task, as well as balance control testing. The results reported in manuscript 1 show that OPTIMAL Theory does have a significant impact on the learning and retention of knee flexion and hip-knee alignment when compared to the control group. The results in manuscript 2 show that the OPTIMAL Theory group transferred the more advantageous movement to a related task, even though no specific instructions were given. The

results in manuscript 3 show that using OPTIMAL Theory-rooted instructions to alter movement in a dynamic task may not transfer to a static task. Collectively, these data suggest that OPTIMAL Theory can be used with dynamic, sport-based tasks to enhance lower extremity biomechanics that are known to relate to ACL injury risk, setting the stage for its inclusion in ACL

# IMPLEMENTING OPTIMAL THEORY IN LOWER EXTREMITY TASKS TO REDUCE RISK OF INJURY

by

Mackenzie Ann Pierson

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Approved by

_____________________
Committee Chair

**Dedication:**

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# CHAPTER I

# INTRODUCTION

In the NCAA, anterior cruciate ligament (ACL) injuries account for the most sport participation time lost relative to all other tracked injuries (Agel et al., 2016). One in 29 female athletes and one in 50 male athletes ruptured their ACL when investigating at 25-year period (Montalvo et al., 2019). There are between 100,000 to 200,000 ACL tears annually in the general and athletic population combined (Rayan et al., 2015). An ACL injury can have many negative consequences. It can sideline an athlete for 12-14 months from activity (Nagelli & Hewett, 2017), although it has been suggested that athletes may have more favorable outcomes if they wait approximately two years before returning to activity (Nagelli & Hewett, 2017). ACL injuries can also have a heavy financial cost, which equates to billions of dollars in health care costs annually (Mather et al., 2013). Lastly, the impacts from sustaining an ACL injury include long-term disabilities such as arthritis (Eichner & Beynnon, 2019), decreases in strength and range of motion (Nguyen et al., 2017), and a greater risk of sustaining an additional ACL injury (Montalvo et al., 2019).

There are four main categories of risk factors for ACL injury: neuromechanical, hormonal, genetic, and anatomical. Neuromechanical risk factors include kinematics, kinetics, and the timing of magnitude of the muscle activation and force production (Shultz et al., 2015). Hormonal risk factors are focused on sex-steroid hormone concentrations which likely underlie many of the sex-specific characteristics that emerge during puberty. A large focus in this line of research is evaluating the menstrual cycle to assess changes in ACL injury risk factors (Shultz et al., 2015). Anatomical risk factors focus on structural differences between those affected by ACL injury (or those who may be at risk of injury) and those who have not had an ACL injury (Shultz et al., 2015). Genetic, the newest category in risk factor assessment, examines differences in genetic profiles that may be associated with ACL injury risk (Shultz et al., 2015). While all four categories contribute to a person's risk profile, genetic, hormonal, and anatomical risk factors are generally considered non-modifiable. Neuromechanical factors are considered modifiable due to the ability to alter movement patterns through training, which is the basis on which current ACL injury prevention programs (IPPs) were founded.

ACL injury prevention programs (IPPs) were designed and implemented beginning in 1996. While some success has been observed in ACL IPPs reducing injury rates in the studied sample (Nessler et al., 2017; Padua et al., 2018), overall ACL rates across the population have not declined (Agel et al., 2016; Tadlock et al., 2019; Weitz et al., 2020). This could be due to a lack of adoption (or improper implementation if adopted) across a wide spectrum of athletes with respect to age, sport type, and sex; but also potentially due to the lack of adoption of newer motor learning principles known to enhance motor learning (Benjaminse et al., 2015a).

Additionally, current ACL IPPs commonly do not test for the retention of lower extremity alignment (a known ACL risk factor) or retention and transfer of proper lower extremity mechanics (Onate et al., 2001; Padua et al., 2012; Prapavessis et al., 2003). Most programs still used today were published between 1996-2008, and little-to-no changes have occurred in these programs since their inception. This is in part due to the time demand of a full intervention study, which can take years to complete. With current programming already existing, a drop-off in intervention studies to test new programs has occurred. Approximately 12 ACL IPPs currently exist, with the Prevent Injury and Enhance Performance (PEP), Knee Injury Prevention Program (KIPP), Knee Ligament Injury Prevention Program (KLIP), and Sportsmetrics being the most widely used. There are sound motor learning concepts already interwoven in current ACL IPP programming such as feedback, practice conditions, transfer of learning, and procedural learning. A few common theories that are represented in ACL IPPs can be identified as Adam's closed-loop theory and Schmidt's Schema theory. A relatively new motor learning theory has not been implemented into ACL IPPs, namely the Optimizing Performance through Intrinsic Motivation and Attention for Learning (OPTIMAL) Theory (Wulf & Lewthwaite, 2016). Elements of this theory are beginning to be implemented into some allied health fields (Johnson et al., 2013; Hunt et al., 2017; Park et al., 2015), but it has not received wide attention in the ACL IPP space.

The OPTIMAL Theory consists of a trio of components that purposefully utilizes sound motor learning components to aid instruction and learning environments. The first component of the OPTIMAL Theory is an external focus of attention (EF), which has been shown to positively enhance motor learning, retention and transfer (Wulf, 2013). An EF is utilized by referencing the goal-oriented outcome external to the body rather than the body itself [i.e., an internal focus (IF)] (Wulf et al., 1998). Past research has shown that: (1) an IF is commonly used in ACL IPPs and (2) an EF would be more advantageous in this context (Gokeler et al., 2014; Gokeler et al.,2018). The theory that provides the foundation for EF motor enhancement is rooted in the Constrained Action Hypothesis (CAH), which suggests that focusing internally (i.e., on your body movements) can constrain the motion and reduce performance. This is potentially due to overcorrection of body mechanics at the micro-level and/or using a portion of cognitive recourses to monitor body movement rather than on the action-orientated goal (i.e., getting the ball in the goal). The other components in the OPTIMAL Theory are rooted in motivation and include autonomy of support (AS) and enhanced expectancies (EE). AS refers to the feeling of a sense of control, which can be provided by offering learners the ability to ask questions or request feedback whenever they want. This sense of control aids learning and retention (Wulf et al., 2015). Another component of OPTIMAL Theory, EE, is when the learner feels as though they are average or above average at a skill or task based off of feedback received (McKay et al., 2012). The learner may not be very successful at a particular task, but if they feel they are average or better compared to past subjects, this helps learning and retention (Wulf, 2013). This sense of not being poor at a task can help the learner focus not on how unskilled they are, but on the task at hand. However, most research on the OPTIMAL theory to-date has focused on upper extremity motor learning tasks (Wulf & Lewthwaite, 2016), with very little on lower extremity tasks (Chau et al., 2020; Iwatsuki et al., 2019; Chau et al. 2018). Thus, prior to adopting OPTIMAL theory in ACL IPPs, it is important to first establish its utility to alter lower extremity mechanics relative to known ACL risk factors.

To address this challenge, I conducted two studies that led to this dissertation. For the first study, data were collected on 75 subjects to evaluate the extent that OPTIMAL Theory could be applied to the lower extremity in the relatively simple task of a squat. Our study included groups of participants who received squat instructions that included all three components of OPTIMAL Theory (EE, EF, and AS group), a combination of two of the components (EE and EF; EE and AS, or EF and AS groups) or no instructions (control group). Participants performed the squat intervention on day 1 and were tested for retention on day 2. Data showed that hip-knee alignment (a known ACL injury risk factor) was enhanced the most after the intervention in two groups: (1) the group who received all three components of OPTIMAL Theory (EF, EE, and AS) and (2) the group who only received EF and AS. While both groups showed enhanced hip-knee alignment, the OPTIMAL Theory group exhibit better alignment than the EF and AS group (Pierson et al., 2019). Participants also performed a transfer test that included a depth drop. Similar to Pierson et al. (2019), the groups who received all three components of OPTIMAL Theory (EF, EE, and AS) or just two components (EF and AS) transferred their newly adopted lower extremity biomechanics from the squat task to the depth drop (Pierson et al., 2020). Thus, for learning and transfer effects relative to the simple lower extremity task of a squat, OPTIMAL Theory (two or three components) led to the strongest desired effects. In a second study—which was pilot data for this dissertation— we expanded the previous study by using a more dynamic and ecologically valid task. Participants hip-knee alignment was measured while performing a basketball rebound. For this pilot study, five participants received task instructions aligned with the three components of OPTIMAL Theory, whereas five participants received no task-relevant instructions (i.e., control group). The data showed that the OPTIMAL Theory group had enhanced hip-knee alignment relative to the control group, $F(2,16) = 11.250$, $p=0.006$. These preliminary results support the postulate that OPTIMAL Theory could be used to reduce ACL injury risk in a dynamic and ecologically valid task, but the study needed to be scaled up to be properly powered.

There are a few gaps in the literature with regard to this topic. First, there is a lack of literature on implementing OPTIMAL Theory in the lower extremity. This theory is still relatively new (2016) and there are not many publications utilizing OPTIMAL Theory in general. The majority of those that have published literature utilizing OPTIMAL Theory are in upper extremity movement tasks (e.g., bag toss, darts) (Wulf et al., 2018; Abdollahipour et al., 2019). Very few have utilized

OPTIMAL Theory in the lower extremity (Chau et al., 2020; Iwatsuki et al., 2019; Chau et al. 2018). No papers have investigated OPTIMAL Theory in the context of ACL IPP tasks. The impact that OPTIMAL Theory has on large movement tasks in the lower extremity remains somewhat unknown. To date, there is no published literature on OPTIMAL Theory implementation to aid injury prevention in the lower extremity. Therefore, there still remains a gap in the impact that OPTIMAL Theory could have in movements related to ACL injury reduction. A second gap in the literature is the extent to which a change in the movement pattern from OPTIMAL theory instructions transfers to related tasks and is retained outside of the initial training period. Understanding the extent to which a movement pattern learned in one task (i.e., a basketball rebound) transfers to a related task (i.e., maximum vertical jump or postural control), as well as the extent to which a single training session "sticks" the following day will help lay the beginning foundation for the adoption of OPTIMAL theory in more sport-related tasks.

To close these gaps, this dissertation had three purposes. The first purpose was to compare performance of an OPTIMAL Theory group to a control in the jump/landing task of basketball rebounding. I hypothesized that compared to the control group, the OPTIMAL Theory group would have increased knee flexion and enhanced hip-knee alignment (both ACL injury risk factors), and these movement patterns would be retained during testing the following day.

The second purpose was to examine the extent to which motor performance transferred from the basketball rebounding task to a maximal effort vertical leap task. I hypothesized that compared to the control group, the OPTIMAL Theory group would have increased knee flexion and enhanced hip-knee alignment, and these movement patterns would be retained during testing the following day.

Lastly, the third purpose of this study was to examine the extent to which enhanced performance learned during a dynamic task (i.e., a basketball rebound) via OPTIMAL Theory instructions transferred to a static balance control task. I hypothesized that compared to the control group, the OPTIMAL Theory group would have decreased center of pressure (CoP) total excursion (an indicator of enhanced postural control) and this movement pattern would be retained during testing the following day.

## CHAPTER II

## REVIEW OF THE LITERATURE

### **ACL Injury**

#### ***Structure and Function of the ACL***

The tibiofemoral joint is a synovial hinge joint. It is the combination of the distal shaft of the femur where two convex condyles meet two rounded, concave condyles at the proximal end of the tibia. Within the fossa of this joint, four cruciate ligaments can be found. The shape femoral condyles differ in size and shape. The medial femoral condyle extends more distally and is curved in the transverse plane. The lateral femoral condyle extends more posteriorly. The proximal tibial consists of both a medial and lateral plateau corresponding to its respective femoral condyle (medial and lateral). Both of the plateaus are slightly concave when assessing from medial to lateral. It should be noted that the lateral plateau is slightly convex from anterior to posterior. These plateaus are generally considered to be only slightly concave. They have a much larger radius of curvature than their corresponding condyles. Due to this incongruity and somewhat odd alignment, the knee lacks stability from bone to bone alone. Therefore, the need for the cruciate ligaments is extremely important (Wise, 2015). While each ligament has a role, the ACL limits anterior motion of the tibia (hyperextension). Due to the anatomical location and structure, the ACL limits anterior tibial translation and internal tibial rotation (Wise, 2015).

## Occurrence of ACL Injury

Most movements that occur in daily life tax the ACL, but do not cause injury. However, some movements that are repeated during sport and physical activity stress the ACL enough to cause damage. Approximately 150,000 ACL injuries occur annually in the United States, equating to 7.6 to 17.7 billion US dollars in health care costs (Bell et al., 2017). Females are four to six times more likely to sustain an ACL injury than their male counterparts (Agel et al., 2016). ACL injury is especially present in youth (Dodwell et al., 2014) and Division I athletes (Rugg et al., 2014). One in four youth athletes who suffer an ACL injury will suffer a second ACL injury in their athletic career (Wiggins et al., 2016). ACL injury is an impactful injury that holds ramifications later in life. Of those who undergo ACL reconstruction (ACLr), 79% develop early osteoarthrosis (Holm et al., 2012) and 20% of those ACLr patients will re-tear their ACL or their contralateral limb's ACL within 2 years (Holm et al., 2012). ACL injury is a multidimensional issue with many different approaches to lessen the impact, prevalence, and occurrence of this injury.

While ACL injury can affect all age groups and genders, there are specific age groups and genders that this injury plagues more often. ACL injuries are still the most impactful and devastating lower extremity injury (Nagai et al., 2018). The annual incidence rate in the general population is 1 in 3500; the actual incidence rate in athletic populations is much higher (Evans & Nielson, 2019). ACL injuries occur more often in girls and women compared to boys and men (Gornitzky et al.2017). Typically, younger athletes and high-level athletes are affected at higher rates (Rugg et al., 2014; Wiggins et al., 2016). The importance of understanding the occurrence of ACL injury is a pivotal part for implementation of injury prevention programs (IPPs).

## Mechanism of ACL Injury

While there are differences in the rate at which males and females injure their ACLs, new research has shown that the mechanism behind ACL injury is the same for both (Owusu-Akyaw et al., 2018). The ACL is commonly thought to keep the tibia from sliding too far forward past the femur and protect against rotational stability. This information has been the basis of many studies with the use of cadaver limbs. However, the tibiofemoral joint can be loaded in different ways, which can strain/stress the ACL through a variety of mechanisms. For example, pure tibial internal rotation torque can lead to severe ACL injury. Pure internal tibial rotation has also been shown to increase ACL strain by 117% (Oh et al., 2011). In laboratory settings, the ACL has been shown to rupture with a tibial internal rotation torque as low as 37.4kN (Meyer et al., 2008; Oh et al., 2011), which is a common load for an athlete to produce during sport & activity (Meyer et al., 2008). Anterior tibial forces—a product of many athletic movements common in sport—also stress the ACL. The mechanism for this stress is thought to be inadequate timing in quadriceps activation during landing (Ueno et al., 2017). Similarly, knee kinematics play a role in ACL injury risk. For example, Markolf et al. (1995) showed that in a fully extended knee, ACL force was 150% (180N) of the force that was being applied to the tibia, highlighting the stress placed on the ACL relative to the bone to which it is connected.

### Differences in ACL Injury Prevalence Between Sexes

While it has been well established that girls and women are at a greater risk for ACL injury and have higher rates of occurrence of ACL injury, examining sex-specific differences can spotlight where ACL injury prevention efforts may be the most effective. The most well-researched areas in this context are the differences between the activity/sport (Mountcastle et al., 2007). The highest ACL injury incidence rate for women is observed in lacrosse (0.23 per 1000 athlete exposures), while men have the highest incidence rate in football (0.17 per 1000 athlete exposures) (Agel et al., 2016). It has also been shown that ACL injuries to females occur most frequently by a non-contact injury mechanism (60%), where male ACL injury occurs most frequently by direct contact (59%). In direct comparison sports for soccer, basketball and lacrosse, women sustain ACL injuries at higher rates than men (Agel et al., 2016). From an historical perspective, from 1994-2013, ACL injury rates increased for females between the ages of6-17 years old. Males increased as well, but only between the ages of 6-14 years old and 17-18 years old. Females had a significantly higher incidence rates with the exception of the age range 17-18 years old. There was an annual increase of ACL injury by 2.3%. Females are tearing their ACL more often than males (Beck et al., 2017)

## Risk Factors

An ACL injury is a multifactorial injury. There have been a host of risk factors that are associated with increased risk for ACL injury. While no single risk factor has been determined as “the” risk factor for injury, it is more likely that combinations of these risk factors contribute to an increased risk for ACL injury. To date, there is no single determining test to confirm who will and will not sustain an ACL injury. Participants of the ACL Research Retreat, a reoccurring conference where leading ACL researchers come together to explore and advance the field, have focused on identifying risk factors at past meetings. Four main categories of risk factors have emerged from the last three ACL Research Retreats (Shultz et al., 2012; Shultz et al., 2015; Shultz et al., 2019): 1) anatomical and structure, 2) genetic, 3) hormonal and 4) neuromuscular and biomechanical.

### *Anatomical and Structure*

Risk factors within this domain include ACL morphology, tibial and femoral surface geometry, knee joint laxity and lower extremity structural alignment. Overall, patients who have sustained an ACL injury have been shown to have smaller ACLs in both area and volume (Chaudhari et al., 2009). When comparing males to females, females (who have a known higher risk of injury and prevalence of injury) had smaller ACLs in length, cross sectional area, and volume compared to males. This holds true when adjusted for body anthropometry (Chandrashekar et al., 2005). The female ACL also has less collagen fiber density (Hashemi et al., 2008) and less strain at failure, stress at failure, and modulus of elasticity (Chandrashekar et al., 2006). Tibial plateau and femoral notch are also risk factors to be considered. ACL injured patients have been shown to have lateral posterior-inferior tibial plateau slopes (Hashemi et al., 2010; Everhart et al., 2010; Stijak et al., 2008) and smaller condylar depth of medial tibial plateau (Hashemi et al., 2010) relative to non-injured participants. Females have also shown greater lateral and medial posterior-inferior tibial slopes relative to males (Hashemi et al., 2008; Hudek et al., 2011). Females have also shown smaller coronal tibial slopes (Hudek et al., 2011). Females also tend to have larger Q angles, which has been identified as a risk factor (Mohamed et al., 2012). These anatomical differences relate to joint stress, as larger posterior-inferior lateral tibial slopes have been associated with greater anterior joint reaction forces (McLean et al., 2010), greater anterior translation of the tibia relative to the femur (Dejour & Bonnin, 1994; Giffin et al., 2004) and greater tibial acceleration (McLean et al., 2011). Moreover, a larger slope between the posterior-inferior slope of the lateral versus medial tibial plateau can lead to a greater peak knee abduction and internal rotation angles (McLean et al., 2010).

Femoral notch width has also been widely studied as a risk factor. Through both prospective and retrospective studies, ACL injured subjects have been shown to have a smaller femoral notch width/notch width index (Domzalski et al., 2010; Everhart et al., 2010; Ireland et al., 2001; Laprade & Burnett, 1994; Shelbourne et al., 1998; Souryal & Freeman, 1993; Souryal et al., 1988; Uhorchak et al., 2003). However, when they were compared to males, female femoral notch height is taller and the femoral notch angle is smaller (Chandrashekar et al., 2005). Previous studies have shown that the varying size and shape of the femoral notch may have influence on risk of injury (Hudek et al., 2011) The notch size and shape may be influential to the risk for injury based on angles of pull and the likely correlation to ACL size (smaller ACL have increased risk of injury) (Charlton et al., 2002).

Lastly, anatomical structure can include knee joint laxity. Overall, ACL injured subjects reported higher magnitudes of anterior knee laxity (Scerpella et al., 2005; Uhorchak et al., 2003; Woodford-Rogers et al., 1994), genu recurvatum (Kramer et al., 2007; Myer et al., 2008; Ramesh et al., 2005; Scerpella et al., 2005), general joint laxity (Hewett et al., 2010; Kramer et al., 2007; Ramesh et al., 2005; Scerpella et al., 2005; Uhorchak et al., 2003) and internal rotation knee laxity (Branch et al., 2010). Females tend to have greater sagittal plane knee laxity (Ngugen &Shultz, 2007; Scerpella et al., 2005; Uhorchak et al., 2003), greater frontal and transverse knee laxity (Shultz et al., 2011) and greater general joint laxity (Scerpella et al., 2005; Uhorchak et al., 2003;). Interestingly, greater knee laxity has been associated with high-risk landing strategies which are more often seen in females than males (Shultz & Schmitz, 2009; Shultz et al., 2010). Knee laxity has been associated with differences in hormone profiles, which will be discussed in-depth below.

### *Genetic*

Genetic risk factors, while likely to have an influence, has little research devoted to this area. It is known that ACL injury is a multifactorial condition and that based on familial and case control genetic association studies, genetic variants play a role. There has been a large number of DNA sequences that have been associated with ACL rupture. These include variants within genes that function to encode collagens (Ficek et al., 2013; O'Connell et al., 2015; Posthumus et al., 2009a; Posthumus et al., 2009b; Posthumus et al., 2010) and proteoglycans (Mannion et al., 2014), which are involved in formation of collagen fibril, the basic building block for ligaments. There is still much more to understand about genetics and ACL injury. To date, no genetic test is valid to test for ACL injury probability.

### *Hormonal*

Hormone receptors for estrogen, testosterone, and relaxin have all been discovered on the human ACL (Dragoo et al., 2003; Faryniarz et al., 2006; Lovering & Romani, 2005). This suggests that they are capable of regulating gene expression and collagen metabolism that may affect the ACL and surrounding soft tissues. This knowledge helps aid other studies that have shown associations between normal physiologic variations in sex hormone concentrations across a menstrual cycle that lead to changes in markers of collagen metabolism and production (Shultz et al., 2012), knee joint laxity (Eiling et al., 2007; Shultz et al., 2010; Shultz et al., 2011), muscle stiffness (Eiling et al., 2007) and the muscle stretch reflex (Casey et al., 2014). It was once believed that the risk for ACL injury was increased during the preovulatory phase of the menstrual cycle when comparing it to the postovulatory phase (Beynnon et al., 2006; Myklebust et al., 2003). Hwever, influence from several sex hormones, secondary messengers,mechanical stress and genetic influence, deter those findings. Another hormone of interest is relaxin. This is due to an NCAA D1 study that found females who sustained an ACL tear had higher levels of relaxin compared to those that had not sustained an ACL injury (Dragoo et al., 2011). The rationale from related literature is that relaxin can cause less organization in the collagen structure (Unemori et al., 1993), and less density in the collagen structure (Dehghan et al., 2014; Unemori et al., 1993;); both of which lead to a more lax and weaker ACL. However, there are only small amounts of literature to support this claim in humans. Promising models have been shown with guinea pigs and this may be an opportunity for future research.

### *Neuromechanical*

Non-contact ACL injuries commonly occur from a sudden deceleration while changing direction when running or landing from a jump (Shimokochi & Shultz, 2008). Previous work has shown that an injury mechanism during this rapid deceleration is a rapid knee abduction and internal rotation during the early weight bearing phase after ground contact (Koga et al., 2011; Koga et al., 2010). Other injury factors contributing to injury risk are an extended knee (limited knee flexion) (Boden et al., 2000), excessive knee abduction (Krosshaug et al., 2007; Olsen et al., 2004; Walden et al., 2012), increased lateral trunk motion (Hewett et al., 2009) and a more posteriorly positioned Center of Mass (CoM) (Sheehan et al., 2012). It is important to note that these factors have been identified in both cadaver model (Tavlo et al., 2016; Schmitt-Sody et al., 2015) and human participants (Boden & Sheehan, 2010; Myer et al., 2015; Hewett & Myer, 2018).

Studying landing biomechanics is a common way to examine ACL injury risk. Hewett and colleagues (2005) were one of the first research teams to demonstrate that landing biomechanics can be a prospective risk factor for ACL injury. A full 3D biomechanical assessment was used and determined that large peak knee abduction moments and peak knee abduction angles at initial contact during a drop jump were prospective ACL injury risk factors for young female athletes. It has also been shown that anterior tibial translation increases as demands on the quadriceps increase (Myers et al., 2011; Schmitz et al., 2010). Therefore, the upright position when contacting the ground during early phases of deceleration has been suggested to have an association with the mechanism of ACL injury (Schmitz et al., 2007; Utturkar et al., 2013). Due to females being at a greater risk of injury than males (Agel et al., 2005; Joseph et al., 2013) landing mechanics between genders has been investigated. These investigations revealed that females demonstrated higher rates of knee valgus during landing than males

(Beaulieu & McLean, 2012: Carson & Ford, 2011). It should be noted that Hewett et al. (2005) demonstrated through research findings that knee valgus may be a potential key biomechanical factor in defining female specific ACL injury mechanics. Much of Hewett's work is rooted in valgus as a risk for injury. Positioning of segments of the body proximal to the knee may also place the knee joint in a high-risk position. Trunk position has been implicated as a risk factor, especially in college age females (Zazulak et al., 2007). To provide a more clinic-friendly tool to identify ACL injury risk based on Hewett et al. (2005) work, the Landing Error Scoring System (LESS) was developed. The LESS is a count of landing technique errors of readily observable items of human movement. A higher LESS score indicates poor technique in landing from a jump. A lower LESS score indicates better jump landing technique (Padua et al., 2009). The LESS is commonly used for jump-landing-rebounding tasks. It was shown that that those who later went on to sustain an ACL injury did have a lower LESS score compared to others (Padua et al., 2009). However, it should be noted that LESS scores did not predict ACL injury in college aged athletes (Padua et al., 2015).

While landing kinematics of the body have been shown to be important risk factors, so too are the associated kinetics, namely the vertical ground reaction forces (vGRF). Studies have shown that the more upright a person is during athletic movements, the higher the vGRF (Bates, 2013; Lisee et al., 2019). This is extremely important as observed from cadaver and computer-based models; strain of the ACL is related to maximal load and timing of GRF (Cassidy et al., 2013;

Cerulli et al., 2003). The neuromechanical risk factors are the most modifiable risk factors with respect to training. Neuromechanical risk factors, therefore, are the focal point for reducing risk of injury.

## Variables of Interest

Within the category of neuromechanical risk factors, there are two variables that are of interest—knee flexion and hip-knee alignment. Both are attainable to collect and monitor without a laboratory setting and have been listed as injury risk factors (Shultz et al., 2015, Shultz et al, 2019). Increasing knee flexion and better hip-knee alignment at landing are common goals in ACL IPPs (Liebert, 2016; Pappas et al., 2016; Lopes et al., 2018; Whyte et al., 2018) and some programs have shown an enhancement in these variables after training (García et al., 2020).

The first variable—knee flexion—is defined as the flexion or decreased angle between the femur and tibia at the knee joint (Schache et al., 2006) and is commonly taken at the bottom of the movement (i.e., end of the downward portion of a squat) to record maximal flexion. It is generally considered that greater knee flexion is advantageous relative to ACL injury risk because it provides greater time for the ligaments in the knee to dissipate the force (Dewig et al., 2020; Hron et la., 2020; Leppänen et al., 2017). When landing from a jump, the physics concept of impulse describes the force-time curve. The total impulse remains the same when jumping from a given height, but since impulse is the product of force x time, either variable can be manipulated to produce the same impulse. Thus, if someone lands with a deeper knee bend (i.e., increased flexion), that increases the amount of time in the equation, so the peak force can remain relatively low. From an ACL injury perspective, this is advantageous because less force must be dissipated by the knee ligaments. Conversely, landing with less knee flexion makes it a “harder” land (i.e., less time equating for more force), which is more harmful to joints and surrounding structures (Hron et la., 2020; Leppänen et al., 2017). Thus, ACL IPPs commonly focus on increasing knee flexion at landing.

The second variable of interest—hip-knee alignment—is the extent to which the knees are aligned with the hips at a defined point in the landing. Hip-knee alignment, though somewhat controversial, has been cited as an ACL injury risk factor repeatedly (Numata et al., 2018; Leppänen et al., 2017; Bourne et al., 2019; Fox et al., 2018). Moving in an unaligned hip-knee pattern can cause strain on ligaments within the knee, making them vulnerable for injury. (Numata et al., 2018). In proper alignment during a landing task, the knees should be directly under the hips when measured in the frontal plane. The knees can go into valgus (inward) or varus (outward) which, could lead to injury (Lin et al., 2012). Hip-knee alignment is typically measured at the lowest point of the movement, as that is when poor alignment is typically the greatest, reflecting maximal knee ligament stress and therefore injury risk (Ford et al., 2003). Hip-knee alignment is presented as a ratio and calculated via the following equation:

$$\frac{\textit{Hip width distance} - \textit{Knee separation distance}}{\textit{Hip Width Distance}}\ X\ 100 = \textit{Hip} - \textit{Knee Alignment}$$

Where hip width distance is measured in cm from anterior superior iliac spine on both sides of the body in a straight line across the pelvis and knee separation distance is measured in cm from the center of the patella; both measured in the frontal plane. While this variable can be measured at any point in the movement, quantifying hip-knee alignment at the lowest point in the movement is likely the most meaningful to assess ACL injury risk. A value of 0% represents perfect alignment, whereas values greater than that represent the magnitude of misalignment. If only magnitude of alignment is of interest, the absolute value of this ratio can be reported. However, if the directionality (i.e., valgus or varus) is of interest, then the positive or negative sign of the ratio should be reported.

### ACL Summary

The ACL, one of four ligaments in the knee, plays a critical role in stability. Stability in the knee allows for rapid change of direction and powerful side to side movement that is commonly seen in sport. Based on previous research, four categories of risk factors for ACL injury have been identified (anatomical/structure, hormonal, genetic and neuromechanical). Neuromechanical risk factors are the most modifiable based on training and have been the focal point for injury prevention programs to help reduce the risk of injury

## Anterior Cruciate Ligament Injury Prevention Programs

Anterior cruciate ligament (ACL) injury prevention programs (IPPs) are designed with the goal to decrease incidence and decrease the prevalence of ACL injury for those that participate (Huang et al., 2020; Joy et al. 2013). While many risk factors have been identified for ACL injury, not all are modifiable. ACL IPPs focus on those risk factors that can be modified to best negate injury (Trojian et al., 2017). The rise of ACL IPPs began in the 1990s and appears to have peaked in the mid to late 2000s (ZBrojkiewicz et al., 2018). ACL IPPs have evolved since inception in the mid-1990s (Grimm et al., 2015), but there has been a lack of recent publications and alterations to current programming.

## History of ACL IPPs

With the passing of Title IX in 1972, an increase in girls and women participating in sports and physical activity occurred. With this rise in participation, there was an increase in injuries that affected both genders differently. By the mid-1990s, researchers were taking notice of concerning injuries to both genders in sport. Therefore, in 1996, Caraffa and his team created one of the first ACL IPPs utilizing proprioceptive training in male soccer athletes. It was reported that the training that athletes participated in significantly reduced the incidence of ACL injuries in the soccer population from 1.15 per team in the control group and 0.15 per team in the trained group (Caraffa et al., 1996). These findings spawned new programs with novel training techniques.

Hewett et al. (1996) and Hewett et al. (1999) were the next researchers to investigate ACL injury prevention. The difference between Hewett et al. (1996) and

Caraffa et al. (1996) is Hewett et al. (1996) utilized jump training and plyometric exercise. Similar to Caraffa et al., (1996) Hewett et al., (1996) also found decreased impact forces and increased hamstring torque in the trained group, along with a lower incidence of ACL injury occurred per 1000 occurrences (0.12 in training, 0.22 in control). This led Hewett and his research team to further investigate the effect of a training with a multifaceted approach which included warm-up, strengthening, plyometric training and agility. Hewett et al. (1999) then evaluated the effect of neuromuscular training on the incidence of knee injury in athletes, both male and female. Between the three groups (control – M & F and training -F), there were 14 serious knee injuries of the 1263 athletes (10 untrained, 4 trained). Knee injury incidence per 1000 athlete exposures was 0.43 in untrained females, 0.12 in trained females, 0.09 in male athletes. Untrained female athletes had a 3.6 times higher incidence of knee injury than trained females, and 4.8 times higher incidence than males (Hewett et al., 1999). These three investigations set the stage for the next round of programs that were implemented. From these three programs, patterns in what was successful and what was unsuccessful began to emerge. The data showed that plyometric and jump/land training were successful at reducing ACL injury risk factors. Hamstring strengthening and control appeared to aid the body while negating ACL injury. These findings laid the foundation for further ACL IPP advancement.

In the 2000s, many programs were developed and implemented in various athletic populations. Heidt et al. (2000), Myklebust et al. (2003), Mandelbaum et al. (2005), Peterson et al. (2005), Olson et al. (2005), Pfeiffer et al. (2006), and Soligard et al. (2008), Herman et al. (2008), and Ghilchrist et al. (2008) were some of the most popular and promising studies that continued to investigate IPPs. Programs during this time were expanded to encompass a warmup and some to all of the following: balance, strength, proprioception, flexibility, plyometrics, jump/landing technique, agility training and endurance training. With the advent of so many programs, it became unclear as to which components were aiding injury prevention. Pivotal meta-analyses by Yoo et al., (2010) and Sugimoto et al., (2014) examined these components along with timing, length of program, and age at implementation in relation to aiding injury prevention. Based on programs prior to 2010, components that had a larger impact on reducing ACL injuries were plyometric training, neuromuscular training, and strength training. It was also determined that younger athletes (under 18 years old) were aided more than other athletes (over 18 years old), likely due to established movement patterns. The duration of training should be between 20-30 minutes, occur several times a week, and implementing programs during a pre-season and regular season is the most beneficial (Yoo et al., 2010; Sugimoto et al., 2014). Between 2000 and 2010, large strides were made in ACL IPPs. Established “knowns” began to be accepted and implemented.

In the last ten years, relatively fewer ACL IPPs have been developed (Kianai et al., 2010; LaBella et al., 2011; Walden et al., 2013), but the problem of ACL injury is very present and still growing (Chen et al., 2019). Over the past 13 years, there has been a 59% increase in the number of required reconstruction procedures, meaning surgery is necessary for return to sport, activity or daily living (Herzog et al., 2017). The increase of ACL injuries is the greatest in females 13-17 years old (Herzog et al., 2017). While the release of new ACL IPP programs has slowed, investigation into ACL injury is still ongoing. A shift from program design to how programs are delivered has slowly started to occur. While previous programs utilized motor learning principles in relation to blocking practices and repetitions, more investigation into the most beneficial way to deliver directions has been investigated. Researchers are beginning to examine implementing different components of ACL IPPs utilizing focus of attention and motivational factors (Bejaminese et al., 2015a; Bejaminese et al., 2017; Gokeler et al., 2018; Welling et al., 2017). While many advancements in ACL IPPs have been made, understanding how the components of an ACL IPP can be enhanced using these new strategies may help to further advance the field.

## Components of ACL IPPs

The components of each individual ACL IPP vary slightly and make each program unique. Common components include strength, balance, proprioceptive training, flexibility, plyometrics, neuromuscular training, agility, and endurance training. The largest question that remains today is to what degree does each component influence ACL injury prevention. A handful of meta-analyses have all come to a similar conclusion. While there appear to be many beneficial components, it is currently not possible to choose a singular component that is having the largest influence. ACL injury is a multifactorial injury and prevention must occur in the same manner (Shultz et al., 2015). As mentioned previously, plyometrics, neuromuscular training and strength training appear to have the largest impact in reducing ACL injury (Yoo et al., 2010; Sugimoto et al., 2014). While other components such as minimizing knee valgus, balance and flexibility hold important influence as secondary components.

To meet the main goal of decreasing ACL injuries, researchers view the same problem through different lenses. The first focal point for ACL IPPs is minimizing knee valgus. The most prevalent research on knee valgus is from Hewett et al. (1996, 1999) and SPORTSMETRICS ACL IPP. Hewett et al., (2005) defined knee valgus as “the position or motion, measured in 3 dimensions, of the distal femur toward and distal tibia away from the midline of the body.” Visually, knee valgus can be described as the collapse of the knee inward. The Hewett et al. (2005) study screened 205 female athletes that were in high-risk sports, where nine (7 soccer, 2 basketball) injured themselves during competitive play. Based on the nine injuries out of the 205 total athletes screened, knee valgus was determined as a contributing and significant risk factor for prospective ACL injury. Those that were injured generated knee valgus moments that were two and a half times greater than those that did not tear their ACL (Hewett et al., 2005). Regardless of the study’s promise, many other studies could not replicate the Hewett et al., (2005) findings (Hashemi et al., 2011; Markolf et al., 1995; Yu &

Garrett, 2007; Yeow et al., 2008). However, knee valgus remains a center point and highly discussed risk factor to minimize, despite the observation that it is rooted in a study with a small sample size that has not been replicated. From a power and performance standpoint, proper alignment can aid power and performance of the athlete (Jackson et al., 2019; Kim et al., 2015; Watanabe et al., 2016). Therefore, while knee valgus continues to be a controversial topic, many programs will likely continue to include it as a focal point, as proper alignment (i.e., limiting knee valgus) aids overall performance.

Strength is a common component and often the first component that is utilized in ACL IPPs. However, strength training alone is not effective in reducing injuries (Yoo et al., 2010). While some programs have shown success without strength as a component (Myklebust, 2003; Peterson et al., 2005; Pfeiffer et al., 2006), programs appear to have more impact when strength is included (Sugimoto et al., 2014). The rationale is that the stronger athletes are, the better control they have of their bodies, and thus they have the ability to negate dangerous movements or stop their bodies from engaging in potentially dangerous movements. Strength is a valuable component in injury prevention and typically aids sports performance as well, which increases compliance in programs (Sugimoto et al., 2012). Based on previous research, strength is now viewed as a building block for ACL IPPs (Huang et a., 2020). With more repetitions and sets of exercises, strength is a likely byproduct. Strength is also a focus point for most ACL IPPs due to its connection with body control. Better strength can equate to better coordination and enhanced proprioception performance (Hewett et al., 2005b; Myer et al., 2009). Many studies have shown that increased hamstring strength in females aids injury reduction, as typically females fire the quadriceps first (Mendiguchia et al., 2011; Myer et al., 2009). Strength, like lower extremity alignment, remains a focal point over many years due to the positive influence operformance. Strength is also highly modifiable. Gains in strength can allow progression of athleticism to occur (Amen et al., 2015).

Neuromuscular training is also a valued and influential component in ACL IPPs (Sugimoto et al., 2014; Yoo et al., 2010;). Aspects of neuromuscular training are included in most IPPs (Caraffa et al., 1996; Gilchrist et al., 2008; Hewett et al., 1999;). The goal of neuromuscular training is to improve the athlete's ability to generate optimal muscle firing patterns, increase joint stability, and to perform movement patterns and skill necessary during activities of daily living and sport activities. Most often neuromuscular training is incorporated through balance exercises, proprioceptive activities on balance/wobble boards, single-leg stability activities, dynamic joint stability exercise, jump training, plyometric exercise, agility drills, and sport specific exercise. Typically, improvements are seen in postural control and side-to-side imbalances that commonly occur in the lower extremity (Caraffa et al., 1996; Gilchrist et al., 2008; Heidt et al., 2000; Heitkamp et al., 2001; Hewett et al., 1999; Hewett et al., 2011; Mandelbaum et al., 2005; Risberg et al., 2001; Soderman et al., 2000; Wilk et al., 2012).

Plyometrics have also been shown to decrease ACL injury risk (Sugimoto et al., 2014; Yoo et al., 2010). Plyometrics focusing on proper technique and body mechanics can aid in reducing serious ligamentous injury. Plyometrics, should, but does not always, teach proper landing and jumping technique. It has been established that when proper technique is taught for landing and jumping, lower vertical ground reaction forces (vGRF) are observed (Hewett et al., 1996). Lower vGRF aids injury prevention by allowing the body to land softer and in more control. Landing as a “spring” instead of hard, with stiff joints, lessens the impact on joints and improves joint health. Proper plyometrics likely also aids injury reduction because it places the body in more sport specific and athletic movements, which the athlete can learn and transfer to sport. While plyometrics, neuromuscular training, and strength training have yielded more influence in injury reduction, other components may still be important.

Jump/landing is a component of most ACL IPPs in some capacity. A common assessment tool used to quantify jump/landing is the Landing Error Scoring System (LESS). While typically used to identify high risk athletes (Padua et al., 2015), the LESS framework has been implemented as part of ACL IPPs since the beginning. Hewett et al. (1996) found that time spent on technique training with landing/jumping can impact components which may lead to ACL injury (i.e., lower vertical ground reaction forces, landing in control). Many ACL injuries occur when an athlete is jumping/landing too stiff or out of control (Padua et al., 2009).

Balance, while often used in combination with neuromuscular training, is not beneficial at reducing injury risk alone (Sugimoto et al., 2014; Yoo et al., 2010;). Earlier literature divided balance into a separate component, and early studies used balance as a singular intervention tool (Myklebust et al. 2000; Soderman et al., 2000;). While they did show some success, it was not as impactful as other components. More recent studies incorporate aspects of balance into neuromuscular training and do not utilize balance as a singular component.

Other components, such as endurance training, flexibility, and agility training are imbedded in other aspects, but are not stand-alone influential pieces in ACL IPPs. While important for athletic performance, endurance training for injury prevention has not been widely implemented in ACL IPPs, but rather is seen as an outcome - fatigue. It is known that neuromuscular fatigue is influential in increasing the risk of injury (Bourne et al., 2019). While the above components are important in negating risk of injury, they have not shown enough singular importance to be studied but can be incorporated with other components. As components are narrowed and combined in the field of injury prevention, it is important to articulate the differences between ACL IPPs in order to identify best practices.

## Areas to Improve in ACL IPPs

Injury prevention programs have only been utilized for roughly 30 years. While this may seem like a lengthy period of time, in reality, it is relatively short compared to other scientific areas studying behavioral change. Therefore, there are areas that ACL IPPs can still be improved upon, which are identified in this section.

In current ACL IPPs, athletes learn movement patterns and motor skills in controlled conditions which rely on neuromuscular feedback mechanisms (Myklebust et al., 2003). This training environment is not similar to competitive practice and play. To allow for a more competitive play atmosphere,  preventative training should focus on interventions that incorporate elements of anticipation, perturbations focus of attention, and visual motor control within complex task environment interactions (Grooms & Oñate, 2016). Allowing the athlete to anticipate a potentially high-risk injury situation may give them sufficient time to avoid the situation. If the time frame is too short to avoid the situation, the athlete can then prepare for the change in direction, upcoming perturbation, or unanticipated movement. Practicing feed-forward mechanisms are important as it allows the athletes time to generate force and control to enhance lower extremity alignment during movement.

Another area of improvement that could advance the field of ACL IPP is transfer. There is currently a lack of transfer from practiced exercises with high conscious control, to the automatic movements required for complex unanticipated events on the field (Benjaminse et al., 2015a, b, c). Having athletes acquire the ability to sustain optimal motor control while engaging the complex athletic movements should be a goal of ACL IPPS moving forward. Currently there is little work done with transfer and ACL IPPs, making transfer a large gap in the field. For this dissertation project, rebounding/jumping will be the primary task, and maximal vertical jump will be the transfer task. While similar to each other, maximal vertical jump is a sport specific task seen in volleyball, basketball, soccer, football and gymnastics. Assessing a higher intensity activity as a transfer task is a great way to see how much was truly able to be applied by the athlete.

Another area of growth for ACL IPPs is to implement the newest research. This is likely one of the largest problems ACL IPPs face. Due to ACL injury being a multifactorial injury, there are many influencing factors that may aid the current IPPs. An easy way to potentially implement motor learning changes is through the use of verbal instruction. Though it has been established that there are more effective ways to teach and learn movement, current coaching (Diefkuss & Raisbeck, 2016; Diekfuss & Raisbeck, 2017; Raisbeck, Yamada & Diekfuss, 2018) and rehabilitation programming (Johnson et al., 2013; McNevin et al., 2000) does not regularly implement these practices. In recent ACL IPP studies, exploring attentional focus has started to appear in selected ACL research, but it is not widely accepted and practiced (Bejaminese et al., 2015b). Motor learning concepts are still used sparingly with respect to ACL IPPs, which allows for a large amount of improvement.

A lofty area of growth for ACL IPPs is rooted in widespread implementation. Currently there is not a multifaceted program that can be applied in different settings that is sustainable over time (Noyes & Barber-Westin, 2018). A program is needed that allows for widespread implementation with high compliance rates and retention over the long term. There is a need to develop and package a preventative training program that can be implemented broadly across different settings through appropriately educated and trained coaches or team leaders to improve compliance and efficacy (Shultz et al., 2015). To assist this widespread implementation, there are components that while difficult, would aid implementation and likely prove successful. Keeping programs low cost and relatively short is ideal (Shultz et al., 2010). Minimizing the gap between those who can afford higher priced training and those who cannot, should not be an influencing factor in injury prevention. It would be advantageous for programs to be low cost and with a managed time duration (Hewett et al., 2006). Another way to ease implementation is to adapt programs based on contextual factors such as sport, age, sex, and skill level (Noyes & Barber-Westin, 2018). As advancements in technology continue to occur, the personalization of programs is more likely. A final way to improve implementation and advance ACL IPPs would be to attempt to embed programs into existing systems (Shultz et al., 2015). Utilizing ACL IPPs as a warm-up and part of conditioning increases compliance and creates a framework that athletes can consistently follow and build upon.

Another way to improve ACL IPPs would be to educate coaches, trainers and others who implement current programming (Diefkuss & Raisbeck, 2016; Diekfuss & Raisbeck, 2017; Raisbeck et al., 2018). As seen in public health areas, education in implementation typically yields larger buy in from communities (Noyes & Barber-Westin, 2018). In an athletics context, buy-in can come from athletes, coaches, athletic trainers, strength and conditioning coaches, parents and administrators. In increase in compliance would likely occur when each stakeholder is educated about the newest principles, why ACL IPP participation is important and its potential outcomes.

### ACL IPP Summary

ACL IPPs have been used for roughly 30 years. Common components include plyometrics, neuromuscular training, balance, proprioceptive training, and strength. In recent years, the components of plyometrics, strength and neuromuscular training appear to have the largest influence in negating injury. While many programs exist, there are main focal points of each program that include: limiting knee valgus, strength and jump/landing technique training. While there have been many advancements in ACL programming, there are still areas of improvement. The largest area of improvement would be to implement (1) ecological validity, (2) transfer and (3) adoption of attentional focus. This dissertation aims to incorporate all three into action. Other areas of improvement that have been discussed—implementation and coaching education—while important and relevant to aid the issue, will not be incorporated into practice through this project.

## Motor Learning Principles and the Application to ACL IPPs

One way to improve ACL IPPs is to incorporate newer motor learning principles and theories into established programs, such as a widespread use of focus of attention, implicit learning, and OPTIMAL Theory. Many ACL IPPs already have certain aspects of motor learning embedded, such as practice blocking, efficiency, repetition, practice times and variability within practice. While these are all helpful in learning new and modified movements, some newer theories could be beneficial if implemented. This section will discuss the benefits of motor learning, how motor learning is currently being utilized in ACL IPPs, and where the deficits are in the application of motor learning into ACL IPPs.

## Beneficial Components in Motor Learning

While sometimes not explicitly discussed, many pieces of the framework for ACL IPPs are rooted in motor learning principles, such as practice scheduling, feedback, motivation, and variability. Within each of the categories, there are important aspects to be discussed and differentiated. For example, practice scheduling encompasses subcategories such as contextual interference, blocked and random practice, repetition, and variability. Contextual interference refers to interference in performance and learning that arises from performing one task in the context of other tasks (Battig, 1956). Contextual interference can lead to a decline in performance during motor skill acquisition, but consequently lead to enhanced motor skill retention and transfer. Contextual interference can be applied through blocked and random practice. Blocked practice is a sequence in which all the trails on one task are done together, uninterrupted by practice on any of the other tasks. The learner concentrates on improving one task before moving on to the next. Random practice refers to when the same task is rarely repeated on consecutive trials, and has been shown to lead to stronger retention relative to blocked practice (Battig, 1972; Morgan & Shea, 1979; Magill et al., 1990; Brady et al., 1998; Brady et al., 2004; Barreiros et al., 2007), making it ideal for in ACL IPPs. Random practice has high contextual iterference and equates to a competitive play atmosphere more than blocked practice (Merbah & Meulemans, 2011; Li et al., 2000; Wright et al., 2004; Merbah et al., 2011).

Another way to view practice scheduling is to look at distributed and massed practice. When longer rest is given between repetitions (distributed practice), improvements in retention occur. The opposite, little-to-no rest time between repetitions (massed practice), does not aid retention (Lee & Genovese, 1988; Magill, 1988). A likely factor that degrades massed practice is fatigue. This can be especially true with large motor movements. However, each type of practice can be beneficial. It is likely that continuous tasks require a longer period to make decisions and appraise the situation, as there is an increased length of time to complete the task. Discrete tasks are relatively short in time and do not require appraisal of situations. Simple choices can be made to best suit the situation (Lee & Genovese, 1988).

Another component of motor learning that would be highly beneficial is feedback. Feedback is an inherently beneficial part of ACL IPPs and a large component of the field of motor learning (Kluger, DeNisi, 1996). Feedback can be intrinsic or extrinsic sources of information for the athletes regarding their performance. Intrinsic feedback is natural feedback, such as vision, audition or proprioception, that is inherent to the athlete after completing the task or movement. Extrinsic feedback, also known as augmented feedback, is also known as performance-related information that is not necessarily inherent. Extrinsic feedback can also aid the athletes as to where their attention should be directed when performing the task (Readdy et al., 2014; Staub et al., 2013).

Extrinsic or augmented feedback is further divided into two subcategories: knowledge or results and knowledge of performance. Knowledge of results is externally presented information to the athlete about the success of a movement or goal-oriented task. Knowledge of performance gives the athlete information about the movement pattern that leads to the performance outcome (Reade et al., 2008; Greenwood et al., 2014). Extrinsic or augmented feedback gives the athletes the information about their success and allows them to determine and develop strategies to enhance their own performance.

Feedback can both positively and negatively influence the learning process and the motivation to learn. When an athlete receives positive feedback after a well performed event, feedback is more beneficial to learning. Negative feedback after a poor event actually enhances the retention of that performance (Chiviacowsky & Wulf, 2007). Receiving positive normative feedback informs an athlete that he/she is performing better than the average athlete at the same or similar task. This enhances learning and retention and is similar to the motivation element, enhanced expectancies. When an athlete receives negative normative feedback about a poor performance that was worse than their peers, his/her retention and learning are lessened (Sigrist et al., 2013; Adams et al., 1972; Sullivan et al., 2008). However, receiving no feedback at all, not positive or negative, is the most detrimental to an athlete's performance (Lewthwaite & Wulf, 2010). There appears to be a connection between feedback and motivation, likely due to the innate social comparison of athletes and their competitive nature. This also spawns amotivation when no feedback or judgement occurs (Carpentier & Mageau, 2016).

Another beneficial component of motor learning is motivation. Motivation may play a key role in feedback and learning, which relates to the self-determination theory. The self-determination theory provides an overall understanding of the types of motivation and their influences on an individual (Deci & Ryan, 2008). To further subdivide this theory, there are two types of motivation discussed: autonomous and controlled motivation. Autonomous motivation is made up of intrinsic motivation and aspects of extrinsic motivation. An athlete can identify with an activity's value and integrate it with his/her own sense of self. Controlled motivation consists of external regulation (i.e., incentive or punishment) and introjects regulation (i.e., shame, self-esteem). Both types of motivation can influence an athlete's behavior. Autonomous motivation tends to show better performance results and retention of movements (Deci & Ryan, 2008). Both can be beneficial in ACL IPPs.

Another component of motor learning that is beneficial in ACL IPPs is variability. Constant practice involves completing a movement in the same matter and under the same conditions each time it is performed (Breslin et al., 2012; Shoenfelt et al., 2002;). Variable practice involves completing a task in a variety of ways under different codnditions (Shea et al., 2001; Landin et al., 1993; Breslin et al., 2012; Shoenfelt et al., 2002; Sherwood et al., 1996; Czyź et al., 2019; Hinkel-Lipsker et al., 2017). In skill acquisition, constant practice outperforms variable practice. However, when assessing transfer tasks, variable practice outperforms constant practice (McCracken & Stelmach, 1977; Shoenfelt et al., 2002; Yao et al., 2009).

Constant and variable practice can be explained by the schema theory (Schmidt, 1975). The schema theory states that knowledge is organized into units. Within the units of knowledge is stored information. A schema is a generalized description or a conceptual system for understanding knowledge, how knowledge is represented, and how it is used. The schemas are used to create parameters for the general motor program. Therefore, variable practice enhances the development of schemas for the athlete to become more proficient and effective at the practiced task.

When combining two areas of a broad field, there are challenges. Some aspects of motor learning fit seamlessly into ACL IPPs or have already been a pivot piece of framework for the success of an IPP. However, there are aspects that have not been implemented well or there is a lack of knowledge in how they are being implemented. As previously discussed, in an ideal world, there would be a way to streamline an ACL IPP to make the implementation of it seamless. There is limited research as to what information athletes are receiving during ACL IPPs (Bejaminese et al., 2015a). While most researchers have acdcepted that the use of an external focus of attention would benefit athletes learning and retention better than an internal focus of attention, little research has been done to evaluate which is being used in current programing. A systematic review (Pierson, Rhea, & Raisbeck, in progress) evaluated what type of attentional focus was being used and the majority of programs used an internal focus of attention and some use mixed methods (i.e., both internal and external focus of attention). However, no program used an external focus singularly. This raises a deficit in current programming that implementing an external focus of attention, while beneficial to the athletes learning, is challenging. While utilizing an external focus of attention in ACL IPPs is ideal, there is no current education to accompany programs to educate those that distribute and run IPPs.

## Motor Learning Summary

Motor learning theories are already being used by ACL IPPs in the framework on which most programming is structured. However, with the rise of newer literature in the field of motor learning since the last original ACL IPP, implementation of the newest information is challenging. An investigation into how motor learning elements are utilized highlights some of the current deficits in IPPs. Literature supports the use of an external focus of attention into current programing, but a lack of information on how instruction is given is a barrier.

Systematically testing the utility of different focus of attention instructions when performing an ecological valid task and performance transfer to a related task are the logical next steps for ACL IPPs to best utilize motor learning theories.

## External Focus of Attention

Attentional focus has been heavily studied for the past 20 years (McNevin et al., 2003; Wulf et al., 1999; Wulf et al. 1998; Poolton et al., 2006; Neumann, 2019; Piccoli et al., 2018; Wulf, 2013). External focus of attention is the focus on the effect of the movement on the environment and/or on an external target rather than your own body in motion. For example, to get the athlete to keep the hips back in the descent of a squat, an external focus of attention cue would be, “Imagine touching your shorts to the back wall on the descent.” In contrast, an internal focus of attention (i.e., focusing on their own body in motion) would be, “Push your hips back as you lower yourself.” While the phrasing is similar, referencing the athlete’s body rather than a movement outcome/external to the body has been shown to make large differences in performance (Diekfuss et al., 2016; Diekfuss & Raisbeck, 2016; Harris et al., 2019; Wulf, 2013;). The use of an external focus of attention has shown to aid movement effectiveness (e.g., accuracy, consistency, balance) and efficiency (e.g., muscular activity, force production, cardiovascular responses) (Wulf, 2013). External focus of attention has progressed from ski simulators (Wulf et al., 1998, Experiment 1; Wulf et al., 2002) to sport-specific tasks, such as basketball shooting (Zachry, 2005; Zachary et al., 2005), putting (Granados et al., 2010; Poolton et al., 2006), target practice (Diekfuss & Raisbeck, 2017) and swimming (Stoate & Wulf, 2011).

## History of External Focus of Attention

This area of study was first empirically studied via a ski simulator and stabilometer (Wulf et al., 1998). In experiment one for this study, subjects were told to focus on the wheels of the ski simulator rather than their own feet. The second experiment used the stabilometer and instructed subjects to focus on their feet (internal focus of attention) or to try and keep the board level (external focus of attention). Both experiments showed the external focus of attention group outperformed the internal focus of attention group in both learning and retention of the task. This experiment was also a pivotal task, as it showed that an external focus of attention could be transferred to different tasks and still yield benefits. As more instruments of measurement and tasks were used, the use of an external focus of attention has consistently been shown to enhance motor learning and retention relative to an internal focus (Wulf, 2013).

With the success of external focus of attention in most applications, a theoretical explanation was necessary to continue the advancement of this field. At first, the explanation for the success of external focus of attention was explained by Prinz’s (1990, 1997) common coding theory of perception and action. The theory states that there is a common brain representation for perception and action. Both refer to a distal event making this format the only format that allows for commensurate coding. Therefore, movement was more effective when they were planned in terms of their intended outcome or effect (external focus of attention) rather than specific movement patterns (internal focus of attention) (McNevin et al., 2003; Wulf et al., 1999; Wulf et al. 1998; Poolton et al., 2006; Neumann, 2019; Piccoli et al., 2018; Wulf, 2013). However, the theory does not specifically predict the differential learning effects of external and internal attentional focus. Thus, it cannot adequately explain the underlying mechanism.

The constrained action hypothesis (CAH) (Wulf et al., 2001a; Wulf et al. 2001b) proved to be a different explanation that could be tested. When a subject or athlete utilizes an internal focus of attention, there are constraints placed on the motor system that interfere with automatic control processing. Using an external focus of attention promotes a more automatic mode of control by utilizing unconscious, fast, and reflective control processes (Park et al., 2015; Wulf, 2013). Other studies have also found similar results with the CAH. For example, there have been associations of external focus of attention with instructions and various measures of automaticity, which has demonstrated reduced attentional-capacity demands (Wulf et al., 2001a), high frequency movement adjustments (McNevin et al., 2003; Wulf et al. 2001a), and reduced premovement times (Lohse, 2012).

While the CAH is still believed to be a strong rationale of why an external focus of attention yields better results than an internal focus of attention, a new expansion on this tries to answer why only one- or two-word differences in instruction can have such a large effect on performance. This is believed to be linked to the self-invoking trigger theory. The theory states that when there is a reference to one's own body, the participant is assumed to facilitate access to the neural representation of the "self" and this may result in self-evaluative and self-regulatory processing (Bargh & Morsella, 2008; Chartrand & Bargh, 2002; McKay et al., 2015; Wulf et al., 2016). Words and directions that trigger the self also trigger neural activation in the self-system (internal focus of attention) and may result in micro-choking episodes which untimely degrade performance (Wulf & Lewthwaite, 2010).

While the history of an external focus of attention is relatively short and the rationale behind why an external focus of attention is successful is still not concrete, there are hundreds of studies that show an external focus of attention yields better performance than an internal focus of attention, which have been examined in recent systematic and meta-analyses.

## Systematic & Meta-Analyses

A number of systematic and meta-analyses have examined the use and application of an external focus of attention. Due to the large number of studies that are examining this application, a systematic review and meta-analyses provide a clear view to examine the overall impact of an external focus of attention.

The first review in this area (Wulf, 2013) outlines the varying areas where the external focus of attention outperformed those in internal or control groups. Through the review, Wulf addressed studies that found conflicting results (i.e., internal outperforming external focus of attention) and discussed why these findings may have occurred due to errors in methodology. The overwhelming consensus in this review is that the use of an external focus of attention aids performance in accuracy, balance, muscle activation and movement kinematics. However, this review was not systematic, nor did it adopt a meta-analysis approach.

A systemic review that evaluated the use of an external focus of attention was performed by Park et al. (2015). In the 18 studies included for review, 83.3% of them showed that an external focus of attention aided performance more than an internal focus of attention. In 11.1% of the included studies, neither internal nor external yielded different results. The results where no instruction yielded better performance compared to external focus and internal focus was 5.5% of included studies. This study examined in more depth the effectiveness of an internal and external focus of attention based on current and past studies.

A recent systematic review and meta-analysis examined balance tasks specifically. Kim et al. (2017) reviewed 790 articles and 16 were included the study based on the inclusion criteria. In general, the results suggested that the external focus of attention yielded better balance learning when compared to internal focus of attention. The meta-analysis showed that the external focus of attention groups outperformed the internal focus of attention groups in the acquisition phase (*ES*= 0.48, *n*= 16; *CI*95%= 0.07 to 0.90, *Q*= 68.7, $I^2$= 78.2%), retention phase (*ES*= 0.44, *n*= 17, *CI*95%= 0.14 to 0.74; *Q*= 26.1, $I^2$= 38.6%), and transfer phase (*ES*= 1.41,

$n$= 4, $CI$95%= 1.00 to 1.82, $Q$= 22, $I^2$= 0%) (Kim et al., 2017).

## Scope of Application

An external focus of attention has been applied to many fields including sports/gross motor (Al-Abood et al., 2002; Granados, 2010; Poolton et al., 2006; Schucker et al., 2009; Stoate & Wulf, 2011; Raisbeck et al., 2018; Raisbeck & Yamada, 2019; Yamada et al., 2020; Zachry et al., 2005; Zarghami et al., 2012; Diekfuss & Raisbeck, 2017) , music (Mornell & Wulf, 2018; Duke et al., 2011), imagery (Yamada et al., 2020), postural control entropy (Rhea et al., 2019), balance control (Diekfuss et al., 2018a; Diekfuss et al., 2019; Diekfuss et al., 2018b), collegiate coaching feedback (Diekfuss & Raisbeck, 2016), duel tasks (Diekfuss et al., 2017), brain function of gross motor movements (Raisbeck et al., 2019) and medical surgery (Mentis et al., 2016). An external focus of attention has shown to have positive influence on skill development and retention (Raisbeck et al., 2015) that can be quantified (Raisbeck et al., 2016). As discussed above, the tasks themselves also range in variety from putting (Granados, 2010; Poolton et al., 2006), dart throwing (Emanuel et al., 2008; Lohse et al., 2010; Marchant et al., 2007; Marchant et al., 2009; Schorer et al., 2012), basketball shooting (Al-Abood et al., 2002; Zachry et al., 2005), a volleyball serve (Wulf et al., 2002), target shooting (Raisbeck & Diekfuss, 2017), to the standing long jump (Porter et al., 2010; Wu et al., 2012). In most tasks the application of an external focus has led to stronger learning, retention and transfer relative to an internal focus. There have been some cases where an external focus of attention has not outperformed an internal focus of attention; however, upon review by other researchers, flaws have been discussed (Castaneda & Gray, 2007). Regardless, the application to many different performance tasks by different research groups has consistently come to the same conclusion that an external focus does aid performance.

Wulf and other researchers have applied an external focus of attention to accuracy tasks, movement efficiency, and movement kinematics. The vast majority of research revealed that the external focus of attention group outperformed an internal focus of attention group (Wulf, 2013). For accuracy tasks, a target was used as a measurement tool. Common accuracy tasks seen in research include hitting golf balls (Wulf et al., 1999; Wulf & Su, 2007), focusing on the intended ball trajectory rather than their own arms (Bell & Hardy, 2009; Wulf et al., 1999; Wulf & Su, 2007) or wrists (Bell & Hardy, 2009). Putting accuracy was also increased with an external focus of attention when subjects were instructed to focus on the putter instead of movements with the hands (Granados, 2010). This aid in accuracy was seen in both novice and experienced athletes (Bell & Hardy, 2009; Wulf & Su, 2007). Accuracy has also been aided with the use of sports equipment. Balls, darts, Frisbees and kicking balls have all been utilized in research. The common act of shooting a free throw was aided by an external focus of attention when the athlete was told to focus on the basket or ball trajectory compared to his/her own body (Al-Abood et al., 2002; Zachary et al., 2005). Volleyball serves, soccer kicks, and soccer throw-ins have also been aided in accuracy with the use of an external focus of attention (Wulf et al., 2002; Wulf et al., 2010; Zachary, 2005).

Accuracy, as previously mentioned, is not the only area where an external focus of attention appears to aid performance. It is also seen in movement efficiency through muscle activation (EMG), maximum force production, speed, and endurance. In an examination of muscular activity, common applications to evaluate were bicep curls (Marchant et al., 2008; Vance et al., 2004;) where subjects were instructed to focus on the bar (external) or on their arms (internal).

Results yielded lower muscle activation with use of an external focus of attention. Muscle activation has also been evaluated in target specific tasks such as a basketball shot (Zachary et al., 2015) and dart throwing (Lohse et al., 2010). Both studies showed reduced EMG activity and increases in accuracy. An investigation into co-contraction of agonist and antagonist muscles where internal and external focus of attention were utilized (Lohse et al., 2011) showed more accurate force production and increase co-contraction between the soleus and tibialis anterior. A lower muscular activity with an external focus relative to an internal focus is associated not only with more accurate force production but also with greater maximal force production (Marchant et al, 2009; Wulf & Dufek, 2009; Wulf et al., 2010).

Movement speed has also been found to be enhanced with the use of an external focus of attention. In reach tasks, shorter movement times and greater peak velocities were found using an external focus of attention (Fasoli et al., 2002). An external focus of attention aiding performance is not limited to land sports. An increased swim speed resulted after asking swimmers to focus on pushing the water back verses focusing on their own movement (Freudenheim et al., 2010). The same results were found with expert swimmers with the use of an external focus of attention in cueing (Stoate & Wulf, 2011). It should be noted that compared to control conditions, the external focus of instruction provided no additional advantages in this case due to the experts' movements being already highly automatized.

Movement kinematics has also been investigated with the use of an external focus of attention. Results showed that movement coordination on a large scale were optimized (Harry et al., 2019; Parr & Button, 2009; Peh et al., 2011; Wulf et al. 2010). Findings revealed advantages in an external group for body coordination patterns and expert ratings of movement. This was evident in an evaluation of rowers when told to “Keep the blade level during recovery” (external) or to “Keep your hands level during the recovery” (internal). This small difference in instruction showed greater improvements in the technique as evidenced by various kinematic measures after a seven-week retention interval (Parr & Button, 2009).

## Summary of EF

External focus of attention has been applied to many tasks and consistently shown that it can enhance performance (Wulf, 2013; McNevin et al., 2003; Wulf et al. 1998; Wulf et al., 2007; Freudenheim et al., 2010; Porter et al., 2010; Abdollaheipour et al., 2015). The scope to which an external focus of attention can be applied is broad and only shows dissimilar results in a few studies. With the overall acceptance from the research community that an external focus of attention likely aids motor performance, there have recently been additions to see what other components might also aid motor performance.

## <u>OPTIMAL Theory</u>

The OPTIMAL (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) Theory was first published in 2016 examining upper extremity tasks utilizing three separate components: external focus of attention, autonomy of support and enhanced expectancies. The goal of this theory was to increase effective motor performance and skilled movement. Wulf and Lewthwaite (2016) describe the need for the OPTIMAL Theory due to theoretical perspectives in recent lines of evidence demonstrating motivational and attentional effects on performance and learning. OPTIMAL Theory is the combination of an external focus of attention, autonomy of support, and enhanced expectancies. Each of these components aid motor performance but in combination create more effective motor performance (Wulf & Lewthwaite, 2016). While the combination breaks through past barriers of singularly evaluating components, a new perspective on learning and retention was a goal of OPTIMAL Theory.

### Components

The OPTIMAL Theory is made up of three components: external focus of attention, autonomy of support, and enhanced expectancies. Autonomy of support and enhanced expectancies act as motivation factors while an external focus acts as an attentional factor. As previously discussed, the external focus of attention has shown to aid performance, learning, and retention in a broad scope of tasks (Wulf, 2013; McNevin et al., 2003; Wulf et al. 1998; Wulf et al., 2007; Freudenheim et al., 2010; Porter et al., 2010; Abdollaheipour et al., 2015). Due to the increases in learning and retention an external focus has had in past research, it serves as an important foundation for OPTIMAL Theory. The remaining two components, autonomy of support and enhanced expectancies, also have a wide variety of literature to support motor performance.

Autonomy of support, or the subject feeling as though they have some control over a situation, is another component of OPTIMAL Theory. Giving individuals autonomy, or control over the environment, can satisfy both a psychological (Deci & Ryan, 2000; Deci & Ryan, 2008) and biological (Leotti et al., 2010; Leotti & Delgado, 2011) need. Human motivation is dependent on the perception of one's actions having effects on the environment (Eitam et al., 2013). Autonomy was identified as a key variable for optimal motor learning (Wulf & Lewthwaite, 2016). Practice conditions that support learners' need for autonomy have consistently been shown to positively affect motor skill learning (Sanli et al., 2013). In studies that examine autonomy of support, it's common for learners to be able to control feedback (Janelle et al., 1997), use of assistive devices (Hartman, 2007; Wulf & Toole, 1999), extent of practice (Post et al., 2014) and frequency of skill demonstration (Wulf et al., 2005). These practices have been found to aid motor learning. Conditionings conveyed through choice or language have been shown to increase individual motivation and performance or learning (Reeve & Tseng, 2011; Wulf et al., 2014). This can be seen in a golf study where participants were allowed to choose the color of the golf ball. This led to more effective learning of the putting task when compared to not giving them any choice in color (Lewthwaite et al., 2015).

The final component in OPTIMAL Theory is enhanced expectancies. Enhanced expectancies is telling the subject they are doing as well, if not better, than others in similar tasks. This is often referred to as false positive social comparative feedback. Dialogue as small as suggesting that the subject will likely do well can increase the learner’s perception of success during practice (Chiviacowsky & Harter, 2015; Palmer et al., 2016; Trempe et al., 2012; Wulf et al., 2012).

The combination of all three components has already been evaluated in pairs (enhanced expectancies & autonomy of support (Wulf et al., 2014), external focus of attention and autonomy of support (Abdollahipour et al., 2017), and external focus of attention and enhanced expectancies (Pascua et al., 2015). All studies evaluating paired components demonstrated that the experimental group (paired components) outperformed the control or singular group (Abdollahipour et al., 2017; Pascua et al., 2015; Wulf et al., 2014;). Therefore, the combination of all three components seems like an effective way to increase motor learning and retention.

## Application of OPTIMAL Theory

Because it's a relatively new theory, OPTIMAL Theory has not had wide implementation. The first study to utilize OPTIMAL Theory applied it to bag tosses with the non-dominant arm (Wulf et al., 2018). There were only four groups in this study, the paired components (3) and the OPTIMAL Theory group. Groups performed a pretest and practiced the task in a blocked fashion (6x10). After a 24- hour retention period, subjects returned for a 10-toss retention test. Results showed that the OPTIMAL Theory group outperformed the paired component groups in both learning and retention of the bag toss task. The authors argue that the use of all three components develop more effective neural connections that support motor performance and learning. It should be noted that no control group was used for this study.

Recently, an investigation of the use of OPTIMAL Theory was evaluated by breaking down each component and giving instruction to convey each component in a singular practice block (Chua et al., 2018). The subject went through six blocks of practice, receiving each instruction for each component two times. The task was maximal vertical jump and the components were counterbalanced between subjects. When compared to a control group, the OPTIMAL Theory group showed benefits beyond jump height when components where "broken up" and given. When components were added, additional jump height increases were seen. This was an important study to evaluate OPTIMAL Theory in an additive benefits lens rather than by whole component. This study shows researchers the ease of utilizing all three components. When all three are implemented at once, it can be a lot for the subject to mentally process and act on.

While continuing to investigate OPTIMAL Theory in the upper extremity, the task of dart throwing was used (Ghorbani, 2019). Results yielded similar findings as previous studies. The OPTIMAL Theory group outperformed the control group on both motor learning and retention testing. However, it should be noted that this study was a small sample size (n=36) and 100% male in the 18-24 age range.

To date, the above studies are the few that have been published using OPTIMAL Theory. This is reasonable as OPTIMAL Theory was only published in 2016. However, the above studies do yield the same results: groups under OPTIMAL Theory outperform singular components, paired components or control groups. While there appear to be promising results with the small amount of published work, obstacles still remain with implementation.

A small number of commentary pieces have been published on OPTIMAL Theory arguing that it is less than “optimal”. Zahir et al. (2018) argued that OPTIMAL Theory is a “sub-optimal” explanation for self-controlled learning advantages because the theory cannot explain all the data clearly. Many predictions rooted in OPTIMAL Theory are not clearly testable, and numerous predictions are not supported by subsequent data. The commentary piece centers around the thought that there is little-to-no evidence supporting Wulf’s claim that self-controlled groups are more “autonomy supportive” than yoked groups (Ste-Marie et al., 2013). The question that is raised is this: Is OPTIMAL Theory a viable explanation for self-controlled learning advantages? Carter and Grand argue that, instead, self-controlled learning advantages arise from more effective information processing associated with performance dependent strategies that ultimately reduce uncertainty regarding task performance (Carter et al., 2014; Grand et al., 2015).

**Barriers to Overcome When Implementing OT**

There are always barriers to overcome when implementing any theory. A large barrier to overcome is the lack of previous publications to see how implementation occurred. There is limited knowledge about the implementation of OPTIMAL Theory, what was successful and what was unsuccessful, due to the lack of current published research in this area. While there are numerous studies that have implemented components of OPTIMAL Theory, the combination of all three poses more challenges. More in-depth evaluations of publications utilizing the paired components will likely aid in OPTIMAL Theory implementation.

A secondary barrier to overcome is rooted in education. Utilizing OPTIMAL Theory requires instruction in order to be able to best implement each component correctly. To date, there is limited availability of educational support for those wishing to implement.

Implementing OPTIMAL Theory in the lower extremity also poses an obstacle. Previous motor learning literature has utilized OPTIMAL Theory in the upper extremity which makes it ideal for tasks such as bag toss, darts, etc. Of the currently published literature on OPTIMAL Theory, the majority take place in the upper extremity. This is also seen in the paired component investigations between external focus of attention, enhanced expectancies, and autonomy of support that have been previously discussed.

## Implementation of OPTIMAL Theory into ACL IPPs

Implementing OPTIMAL Theory into ACL IPPs poses a unique challenge not addressed in the previous section. The largest challenge would be to get current ACL IPPs to agree to implement OPTIMAL Theory into pre-existing programs. The addition of OPTIMAL Theory into pre-existing programs would allow for more structure in feedback and instructional cueing, which is needed as discussed in previous sections. As indicated in the latest ACL Retreat Consensus statement (2015), utilizing an external focus of attention was recommended. OPTIMAL Theory would follow that recommendation as well as add two other motivational components which have been successfully implemented to aid motor performance (Abdollahipour et al., 2017; Pascua et al., 2015; Wulf et al., 2014;).

Beginning to bridge the gap between motor learning and ACL injury research aids both fields. While primarily utilizing an external focus of attention, the studies are producing positive results in motor learning and retention of movements. (Benjaminese et al., 2015a; Benjaminese et al., 2015b; Benjaminses et al., 2015c; Gokeler et al., 2014; Gokeler et al., 2015; Gokeler et al., 2018). It's clear that there is a gap in the literature about ACL injury prevention and OPTIMAL Theory that needs more investigation.

## Potential Influences for OPTIMAL Theory in Application

While our scope of application is directed towards ACL IPPs and other injury prevention aspects, OPTIMAL Theory could be applied to other areas. One area that would greatly benefit would be coaching. However, as with any performance or coaching aspect, there is a relationship component. When implementing the three components of OPTIMAL Theory understanding the player coach relationship is key. OPTIMAL Theory may be best applied with coaches when there is a healthy, accepting relationship between both parties. Two of the variables have a sense of trust interwoven with them as motivational factors, enhanced expectancies and autonomy of support. Delivering instruction with enhanced expectancies poses a challenge because the coach would be giving the athlete a false sense of performance. For the athlete to believe in the instructions they were receiving, a sense of trust or belief must be in place. The same concept is applicable for the other motivational factor, autonomy of support. Having the athlete believe they have some aspect of control in the situation may pose challenges for implementation due to the nature of a player/coach relationship. Ensuring the athlete feels a sense of control may be critical to implement autonomy of support.

Building a relationship between the persons giving and receiving instruction is key in application. While it is somewhat unknown regarding the degree to which this relationship is built during a research setting, there were still successful results seen. However, to best use each component, a relationship between both parties is desired.

## Direction of this Dissertation

There are several gaps that the proposed study design is intended to address. First, the majority of work in this area has focused on relatively static laboratory-based movement tasks. In order to enhance ecological validity, we will provide instructional cues based on OPTIMAL theory during a basketball rebounding task while monitoring lower extremity ACL injury risk factors (hip-knee alignment and knee flexion) when landing from the rebound. Second, the research gap relative to transfer will be addressed by having participants perform a maximum vertical jump after the rebounding practice to determine if similar knee kinematics are adopted in this secondary, yet related, task. Third, a test commonly employed by clinicians to assess balance performance will be used as another transfer test to determine the extent to which movement patterns learned in a dynamic task transfer to a static, somewhat related, task. To address this gap, we will use the Balance Error Scoring System (BESS) test, which is a popular subjective assessment of balance control (Bell et al., 2011; Guskiewicz, 2011). The BESS test will be completed while standing on a portable force plate so that an objective measurement of balance (center of pressure path length) can be captured at the same time as the subjective measurement.

# CHAPTER III

# OUTLINE OF PROCEDURES

## Participants

We recruited a total of 60 young healthy adults (18-35 years) from the University of North Carolina at Greensboro in Greensboro, North Carolina. All participants were screened for COVID-19 symptoms and eligibility based on inclusion and exclusion criteria. Criteria for exclusion included: (1) positive test for COVID-19; (2) previous injury to the lower extremity that altered their daily life in the past six months; (3) any current musculoskeletal injuries or impairments that lead to pain or discomfort while running and jumping; (4) surgery to the knee in the last 12 months; (5) lack of sports participation in basketball, volleyball, football or soccer for a minimum of three years.

Once participants' eligibility was confirmed, we equally randomized subjects into two groups, (1) OPTIMAL Theory and (2) Control. Both groups participated in the same tasks, but with different instructions. The OPTIMAL Theory group was given instruction with the components of external focus of attention, autonomy of support, and enhanced expectancies. The control group was given nothing beyond basic task instruction so subjects could correctly complete the task. All subjects underwent pre- and post-testing on Day 1 and retention testing on Day 2.

## Procedures

All data collection occurred in the Coleman Research Gym at the University of North Carolina at Greensboro's main campus. All procedures for this study were approved by the UNCG local institutional review board prior to collection. Prior to participation, participants were asked to complete an informed consent, demographics questionnaire, and current health standing report. The demographics questionnaire included basic height, weight, age, biological sex, health history, previous injuries to the lower extremity, previous surgeries to the lower extremity and previous sport experience. Once a review of information was complete and met inclusion criteria, the participants began intake preparation for the study.

Intake preparation included placing "X's" at the center of each participants' patellas and on the upper tongue of their shoes. These marks aided in instruction later for the OPTIMAL Theory group. Participants then underwent a dynamic warmup to minimize the risk of injury during testing. Participants were then placed into either the control or OPTIMAL Theory group.

## Study Design

A schematic of the study design is presented in Figure 1 and the details associated with the assessment equipment and associated protocols, along with the procedure for each day presented below.

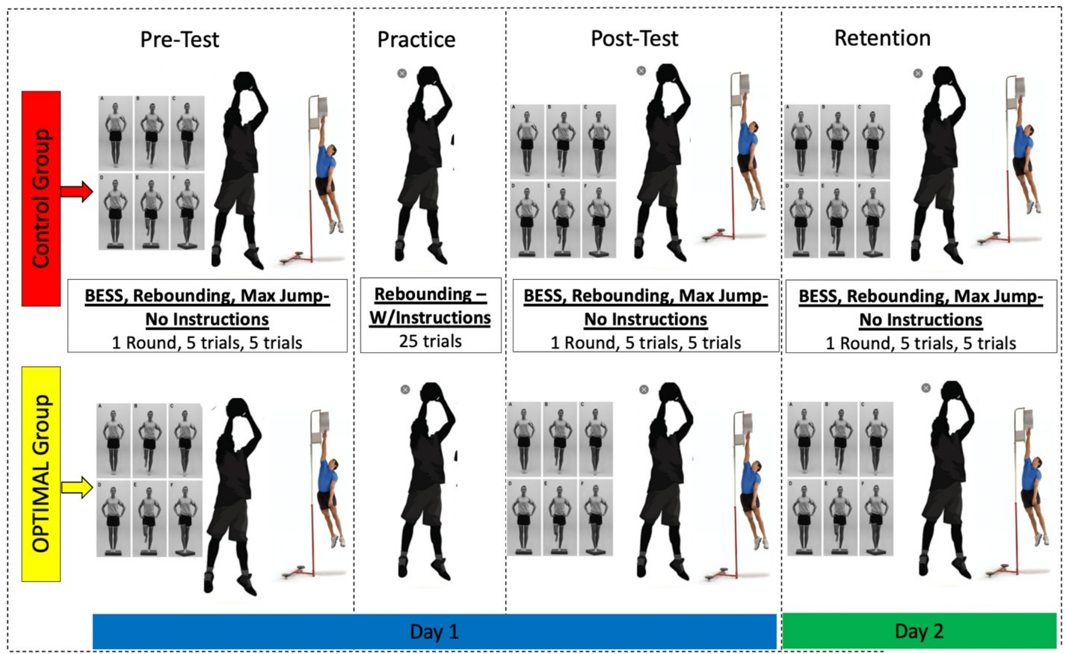


Figure 1. Study Design.

## Assessment Equipment and Associated Protocol

### GoPros

The GoPro Hero 5 cameras were placed 1.2 meters from the participant, performing the rebound drill and maximal vertical leap, one to record a sagittal view and one to record a frontal view. Participants were filmed from the waist down and each participant's knee height to minimize distortion. The video was the source of information to quantify the dependent variables of hip-knee alignment and knee flexion during the tasks. This was accomplished by uploading the video to a computer, dividing and labeling the video by subject and set/repetition and then opening each file in Kinovea to process.

## Tablet

The tablet was used to film practice rounds for the external focus of attention group. Participants were able to see their own knee to hip width differences after each practice round. Film from the practice round was not stored, but deleted after use due to the iPad's programing, "PlayGround Physics", being unable to store the large amount of film per person.

## **Analyze Results**

Our primary data came from video analysis. Video collected using GoPro Hero5 was analyzed using Kinovea (version 0.8.15). Kinovea is a video software program that can process the video based on stills and known measurements. Therefore, determining the distance and angles of movement. The same person analyzed all video (MP) to keep consistency between subjects and minimize between person differences.

## **VERTEC**

The VERTEC is a device that measures the maximum height of a vertical jump. The dependent variables for this task were knee flexion and hip-knee alignment. The maximum jump height was a descriptive variable. This device was used for the maximal vertical jump tests that subjects performed for a pre and post- test on Day 1 and retention test on Day 2. Participants performed five repetitions for the pre, post and retention testing. Instructions were: '*Jump with a* *maximal effort each time*" for each group. Jumps were averaged so there was one resulting data point or each pre, post, and retention testing session.

## **<u>BTrackS Force plate and BESS Test</u>**

BTrackS portable force plate is a lightweight device designed to measure the movement of the CoP during quiet standing, which provides an objective way to measure balance. The BESS test (a subjective balance test) was completed while standing on the BTrackS force plate so that both an objective and subjective assessment of balance can be conducted. The BTrackS force plate measures CoP displacement at 25 Hz for the duration of the text. Congruent with the BESS test procedures, each trial will last 20 seconds. There will be 6 trials, one for each of the conditions of the BESS test: (1) double leg stance directly on the force plate, (2) double leg stance on a foam pad placed on the force plate, (3) single leg stance on the non-dominant foot directly on the force plate, (4) single leg stance on the non-dominant foot on a foam pad placed on the force plate, (5) tandem stance (heel-to-toe with non-dominant foot in back) directly on the force plate, and (6) tandem stance (heel-to-toe with non-dominant foot in back) on a foam pad placed on the force plate (Figure 2). Each condition is completed with eyes closed and hands on hips. For the BESS test, an error is counted if: (1) moving the hands off of the iliac crests, (2) opening the eyes, (3) step stumble or fall, (4) abduction or flexion of the hip beyond 30 deg, (5) lifting the forefoot or heel off of the testing surface, or (6) remaining out of the proper testing position for greater than 5 seconds. The total number of errors on the BESS test (lower equates to better performance) was the subjective balance assessment dependent variable. For the objective balance assessment dependent variable, the CoP displacement was tracked with the BTrackS force plate during each trial of the BESS test.

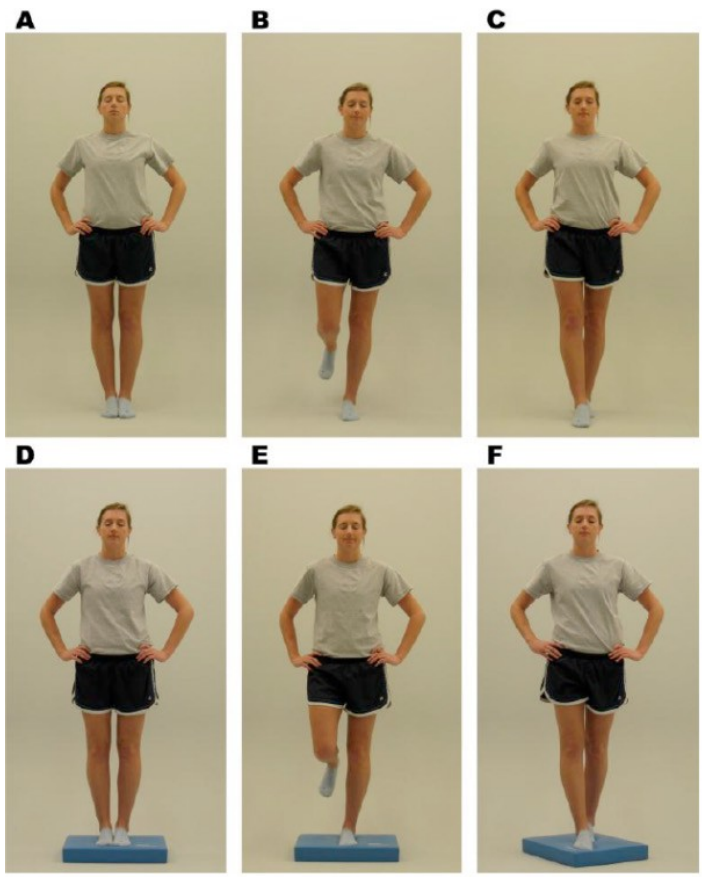


Figure 2. The Six Conditions of the BESS Test.

## <u>Day 1</u>

The control and OPTIMAL groups underwent the same tasks in the same order and were matched randomly for the pre, post and retention testing. For example, the pre-test included three tests (rebounding task, maximal effort vertical jump and BESS testing) that were randomized for the OPTIMAL participant, and that order was matched for a participant in the control. An order may have been as follows. The first task, the BESS test, (static balance test) occurred on the BTrackS force plate. This was followed by a basketball rebounding pre-test. The subjects were asked to jump and rebound the basketball, thrown by the PI, at the top of their jump for a total of 5 pretest jumps. After a 5-minute break, subjects were asked to perform 5 maximal effort vertical jumps using the VERTEC. This concluded the pre-testing portion of the study.

After a second break, 5 minutes, subjects entered the practice block. There was a difference between groups in the practice block. Based on their group assignments prior to pre-testing, subjects underwent the task with little-to-no instruction (control group) or a set of instructions that incorporate the OPTIMAL theory components (OPTIMAL group). The OPTIMAL group received instructions as follows:

"*Jump like a spring and catch the ball at the highest part of the jump. While doing that try to keep the "X's" in alignment. You can ask me for feedback at any point during your trails. You are doing much better than the previous subject*". Instruction will be given at the start of each practice set. After each set of 5 jumps is complete, their trial video will be played on the tablet and shown to the subject so only their legs are seen. This is part of the external focus of attention component, as subjects will be instructed to focus on the "X's" and to try and keep them in alignment.

The practice block consisted of 5 trials of 5 rebounding jumps using the basketball and backboard. After each set of 5, a 3-minute rest period was given where the OPTIMAL group viewed their own hip-knee alignment. At the completion of the 5x5 practice block, a post-test was administered of 5 rebounding jumps.

Participants then performed 5 post-test jumps on the VERTEC at maximal effort, followed by a post-test on the BTrackS portable force plate following the full Balance Error Scoring System (BESS) test. Data were collected on their BESS score as well as center of pressure (CoP) total excursion data.

## **<u>Day 2</u>**

After a 24-hour retention period, participants returned to the lab for testing. Like Day 1, the tape/marker "X's" at the center of their patellas and on the upper tongue of their shoes were placed on the participants. All participants went through the same 10-minute dynamic warm-up led by the PI.

Subjects, regardless of group, performed a retention test for the rebounding task, VERTEC maximal jump, and BESS trials. The rebounding and VERTEC included 5 trials each and a rest period of 5 minutes was given between tasks. The BESS trials were collected after the rebounding and VERTEC tasks.

## **<u>Statistical Approach</u>**

*Purpose #1: T*o compare performance of an OPTIMAL Training group to a control in a jump/landing task of basketball rebounding. I hypothesized that compared to the control group, the OPTIMAL Theory group would have increased knee flexion and enhanced hip-knee alignment (both ACL injury factors), and these movement patterns would be retained during testing the following day. In order to compare performance changes between the control and OPTIMAL Theory group in the rebounding drill for knee flexion and hip-knee alignment, data were averaged per trial for both variables. For each trial (pre-test, post-test, retention), an average was determined for each subject. A 2 (group) × 3 (time period) ANOVA was conducted for knee flexion and hip-knee alignment. As normality is an assumption in ANOVAs, we used the values of +1/-1 to assess skewness and values of +2/-2 to assess kurtosis. A Greenhouse-Geiser correction was used for non-normally distributed data. The alpha value was set $p=0.05$. If significant group × time interactions occurred, a one-way ANOVA was used to determine which group showed differences and a paired samples t-test was then used to determine at which point there are significant differences.

*Purpose #2:* To compare the ability for transfer motor performance from the basketball rebounding task to a maximal effort vertical leap task. I hypothesized that compared to the control group, the OPTIMAL Theory group would have increased knee flexion and enhanced hip-knee alignment (both ACL injury factors), and these movement patterns would be retained during testing the following day. To compare the control and OPTIMAL Theory group in the maximal vertical jump task, averages for knee flexion and hip-knee alignment for pre-test, post-test and retention determined. A 2 (group) × 3 (time point) ANOVA was conducted for knee flexion and hip-knee alignment. Similar to purpose #1, a Greenhouse-Geiser correction was used for non-normally distributed data. The alpha value was set $p$=0.05. If significant group by time interactions occurred, a one-way ANOVA was used to determine which group showed differences and a paired samples t-test was used to determine at which point there were significant differences.

*Purpose #3:* To compare the ability for transfer motor performance from the basketball rebounding task to a static postural control task. I hypothesized that compared to the control group, the OPTIMAL Theory group would have decreased center of pressure (CoP) total excursion (an indicator of enhanced postural control) and this movement pattern would be retained during testing the following day. To compare CoP total excursion (i.e., path length) and BESS balance scores, averages for each trial were determined. The averages were used in a 2(group) x 3(time point) ANOVA. A Greenhouse-Geiser correction was used for non-normally distributed data. The alpha value was set $p$=0.05. If significant group by time interactions occurred, a one-way ANOVA was used to determine which group showed differences and a paired samples t-test was then used to determine at which point there were significant differences.

## Power Analysis

A total sample size was determined by using G*Power (version 3.1). We used previous effect sizes to help determine the total sample population for this study. The following information was used: effect size of 0.40, alpha error probability of 0.05, power of 0.80, numerator df of 1, number of groups 2, and number of covariates of 4. Based on these numbers, a total sample size of 52 was determined, 26 per group. We rounded up to 30 to help increase power and have enough data past what was necessary in case of unusable data.

# CHAPTER IV

# MANUSCRIPT I: AN EXAMINATION OF OPTIMAL THEORY ON KNEE FLEXION AND HIP-KNEE ALIGNMENT IN A DYNAMIC TASK

## Introduction

Anterior cruciate ligament (ACL) injury plagues roughly 1 in 3500 people in the general population every year (Nathan et al., 2020), and it has an even greater impact on athletic populations. For example, ACL injury accounts for the most time lost participating in sport relative to all other tracked injuries (Mueller & Casa, 2011). The average time spent on the sidelines for an athlete who sustained an ACL injury is 12-14 months (Nagelli & Hewett, 2017). However, due to the high re-tear rate, some practitioners have recommended sitting out two years prior to resuming competitive play (Nagelli & Hewett, 2017). The consequences of an athlete forced to sit out can have a financial, emotional, and/or physical impact (Mather et al., 2013; Casebolt, 2018).

Of the four categories of ACL injury risk factors—anatomical, hormonal, genetic, and neuromechanical—only the latter is considered modifiable (Shultz et al., 2015). To this end, ACL injury prevention programs (IPPs) were first developed in the mid-1990s that focused on modifying neuromechanical factors associated with an ACL injury (e.g., knee flexion, hip-knee alignment). While ACL IPPs have shown some success (Huang et al., 2020; Soomro et al., 2016), overall ACL injuries rates have not declined (Beck et al., 2017; Zbrojkiewicz et al., 2018). This could be due to a lack of ACL IPPs being implemented on a large scale and/or implementation that does not meet the original guidance. While those barriers should be addressed, another area of refinement in this space is the manner in which ACL IPPs utilize more recent motor learning theories.

Applying the field of motor learning to ACL injury prevention has shown promising results in movement pattern learning and retention (Gokeler et al., 2018). One theory that is relatively new and not extensively tested is Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) Theory (Wulf & Lewthwaite, 2016). This is a three-component theory that incorporates an external focus of attention, autonomy of support, and enhanced expectancies. Each component of OPTIMAL theory has been previously shown to enhance motor behavior, and the combination of these components when learning and retaining a motor skill has been shown to be even more beneficial (Wulf & Lewthwaite, 2016).

The first component of OPTIMAL Theory is an external focus of attention (EF). An EF has been heavily studied and results have been repeated in the learning, retention, and transfer in numerous movements in the upper and lower extremities (Wulf, 2013). An EF is utilized by referencing the goal-oriented outcome external to the body rather than the body itself [termed an internal focus (IF)] (Wulf et al., 1998). Past research has shown that: (1) an IF is commonly used in ACL IPPs and (2) an EF would be more advantageous in this context (Gokeler et al., 2014; Gokeler et al., 2018). The theory that provides the foundation for EF motor enhancement is rooted in the Constrained Action Hypothesis (CAH), which suggests that focusing internally (i.e., on your body movements) can constrain motor control (Kal et al., 2013). This is potentially due to overcorrection of body mechanics at the micro-level and/or using a portion of cognitive recourses to monitor body movement rather than on the action-orientated goal (e.g., getting the ball in the goal). The other components in OPTIMAL theory are rooted in motivation and include autonomy of support (AS) and enhanced expectancies (EE). AS provides the learner with a sense of control by allowing them to request feedback and/or ask questions when they want. This sense of control aids learning and retention (Wulf et al., 2015). EE is when the learner feels as though they are average or above average at a skill or task (McKay et al., 2012). The learner may not be very successful at a particular task, but if they feel they are average or better compared to past subjects, this helps learning and retention (Wulf, 2013). The sense of not being poor at a task can help the learner focus not on how unskilled they are, but on the task at hand.

While there is data supporting OPTIMAL Theory for the learning, retention, and transfer of motor skills, most studies to-date have focused on upper extremity tasks (Wulf & Lewthwaite, 2016). Those that focus on the lower body have not focused on movements related to ACL injury prevention (Chau et al., 2020; Iwatsuki et al., 2019; Chau et al. 2018). Prior to adopting OPTIMAL Theory in ACL

IPPs, it is important to first establish its utility to alter lower extremity mechanics relative to known ACL injury risk factors. To this end, our previous work first focused on testing the utility of OPTIMAL Theory with a relatively stationary lower extremity task (i.e., a box squat). Our results showed the group that was provided all three components of OPTIMAL Theory showed the most significant change (relative to just two components and a control group) relative to better hip-knee alignment (an ACL injury risk factor) not only in the squat task (Pierson et al., 2019), but also transferred the enhanced neuromechanical characteristics to a related task (i.e., a depth drop) (Pierson et al., 2020). Despite these promising results, it is unclear the extent to which enhanced neuromechanical characteristics can be developed using OPTIMAL Theory in more dynamic and sport-specific tasks. Such an exploration is needed prior to adopting OPTIMAL theory principles into ACL IPPs.

The purpose of this study was to examine the extent to which OPTIMAL Theory may enhance neuromechanical characteristics relative to ACL injury risk in a dynamic and sport-specific task of basketball rebounding. Specifically, we examined knee flexion angle and hip-knee alignment (both ACL injury risk factors) when landing from the jump after rebounding a basketball during one day of instruction, and we tested retention 24 hours later. We hypothesized that the compared to the control group, the OPTIMAL Theory group would have increased knee flexion and enhanced hip-knee alignment after the practice session and that these movement patterns in the OPTIMAL Theory group would be retained during testing the following day.

## Methods

### Participants

A total of 60 young healthy adults were recruited for this study. Participants were randomly assigned to the OPTIMAL (n=30) or the control group (n=30). All participants were between the age of 18-35 years old. Subject demographics can be viewed in Table 1. All participants were screened for COVID-19 symptoms and eligibility based on inclusion and exclusion criteria. Criteria for exclusion were: (1) positive test for COVID-19; (2) previous injury to the lower extremity that altered their daily life in the past six months; (3) any current musculoskeletal injuries or impairments that lead to pain or discomfort while running and jumping; (4) surgery to the knee in the last 12 months; (5) lack of sports participation in basketball, volleyball, football, or soccer for a minimum of three years.

Table 1. Participant Demographics. All variables represented as Mean (SD).

| **Group** | **Age (years)** | **Height (cm)** | **Weight (kg)** | **Sex** |
|---|---|---|---|---|
| *Control* | 22.1 (3.3) | 167.9 (9.7) | 71.6 (16.1) | F=20; Male = 10 |
| *OPTIMAL* | 21 (3.6) | 172.2 (10.9) | 81.0 (22.8) | F=15; Male=15 |

## Experimental Design

A schematic of the study design is presented in Figure 3. This was a 2-day study which collected pre-test and post-test data on Day 1. Retention data were collected after a 24-hour break. Pre-test, post-test, and retention testing included a simulated basketball rebound. Two cameras (GoPro Hero5, San Mateo, CA)—one in front and one on the participant's right side) were used to record lower extremity motion that was later processed using Kinova software to obtain knee flexion angles (sagittal plane) and hip-knee alignment (frontal plane).

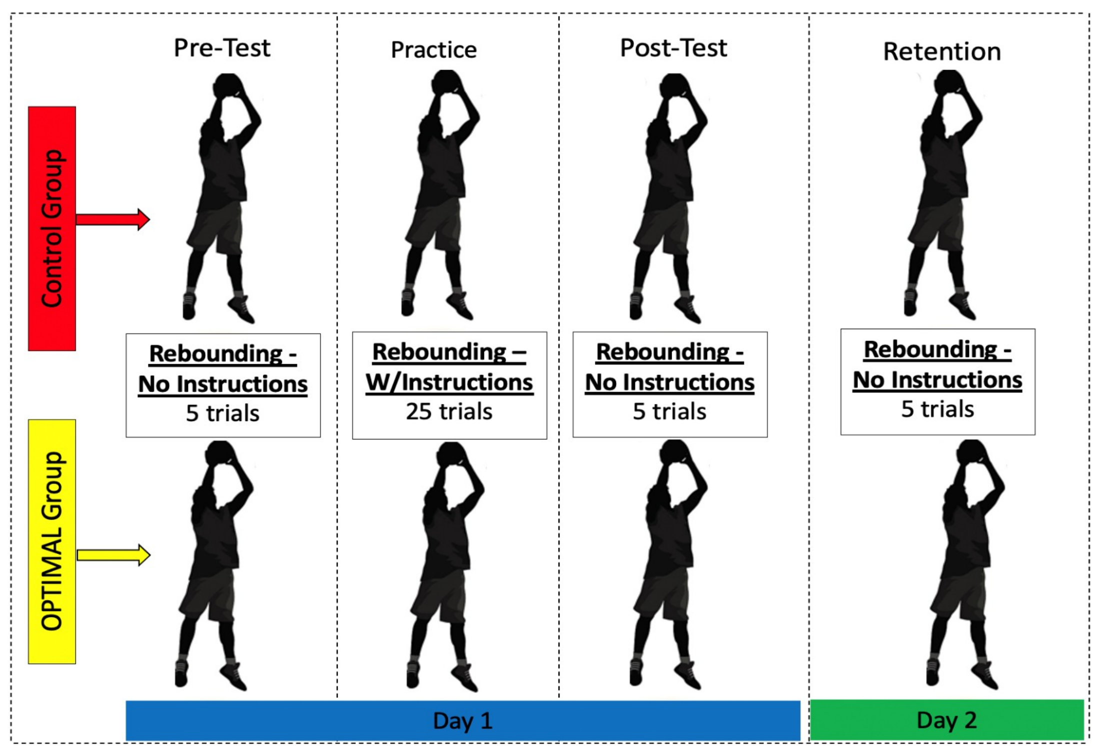


Figure 3. Experimental design.

## Experimental Procedure

Participants were tested in a research gymnasium to best simulate sport specific movements. Within the gym, demographic information was collected, and height, weight, and hip width were measured. A researcher then marked an "X" on the center of the patella of the participant to aid in tracking the participant's movement when processing and to use the mark as a reference during instructions. Next, a researcher led each participant through a dynamic warm-up, after which pre-testing began that included five basketball rebounds with no instructions other than "*Catch the ball at the highest point possible to mimic a rebound*." After pre-testing and a five-minute break, participants moved to the practice block on the study design.

During the practice block, participants performed 25 basketball rebounds using a five rebounds, break, five rebounds, break, etc. structure. During this practice block, participants' instructions varied based on group assignment. The OPTIMAL Theory group's instructions were *"Jump like a spring and catch the ball at the highest part of the jump. While doing that try to keep the "X's" in alignment [EF component]. You can ask me for feedback at any point during your trials [AS component]. You are doing much better than the previous subject [EE component]"*. The control group was only instructed "*Jump and catch the ball at the highest possible point to mimic a rebound*." Instruction was given at the start of each five-rebound practice set. After each five-rebound set, the OPTIMAL group was shown their video of their previous practice round on the tablet. The subjects could only view their hip-knee alignment, all else was blocked. Both groups received three minutes of rest. For the OPTIMAL group, assessing their own hip-knee alignment was part of the external focus of attention component, as subjects were instructed to focus on the “X’s” and to try and keep them in alignment compared to their hips. After the 25-rebound practice block and a break, posttesting began. Post-testing mirrored pre-testing, which was 5 basketball rebounds with no instruction other than “*Catch the ball at the highest point possible to mimic a rebound*.”

After a 24-hour period, participants returned to the research gymnasium. They completed the same warm-up that was performed on Day 1, followed by retention testing that included five basketball rebounds. No instruction was given to either group on Day 2 other than “*Complete the task as you remember from yesterday*”. Cameras were used to capture both frontal and sagittal planes of movement, identical to Day 1.

## Data Reduction

Video from the cameras were uploaded to Kinovea (version 2.2.0), a free 2D motion analysis software for which the validity and reliability has been previously reported (Puig-Divi et al., 2019; Balsalobre-Fernández et al., 2014). Knee flexion angles in the sagittal plane and knee-hip alignment in the frontal plane were computed via the Kinovea software by identifying landmarks on the lower limb previously marked (i.e., malleolus, lateral epicondyle, and greater trochanter).

For the purposes of this paper, knee flexion was defined as the angle of the knee during the lowest point of the landing between the femur and tibia. Hip-knee alignment was defined as the extent to which the knees were aligned with the hips at the lowest point of the landing. Hip-knee alignment is presented as a ratio and calculated via the following equation:

$$\frac{\textit{Hip width distance} - \textit{Knee separation distance}}{\textit{Hip Width Distance}}\ X\ 100 = \textit{Hip} - \textit{Knee Alignment}$$

Hip width distance was measured in cm from anterior superior iliac spine on both sides across the pelvis, and knee separation distance was measured in cm from the center of the patella. Hip width and knee separation distance were measured in the frontal plane. For hip-knee alignment, a value of 0% represents perfect alignment, whereas values greater than that represent the magnitude of misalignment. Since only magnitude of alignment was of interest, the absolute value of this ratio is reported.

All videos for this study were processed by the same person. Only videos from the rebounds during the pre-test, post-test, and retention test were analyzed (i.e., practice block videos were not analyzed as video was not stored after use on tablet due to storage capabilities). Averages were computed within each block. For example, the 5 pre-test jumps for a participant were converted into one singular average which represents the entire pre-test. The same was done for the post-test and retention test.

## **Statistical Analysis**

Separate 2 (group) × 3 (time period) repeated measures ANOVAs were used to examine changes in knee flexion and hip-knee alignment across the pre-test, post-test, and retention test. Alpha level was set to *a priori* at 0.05. To reduce type I error, Mauchly's test of sphericity was used and a Greenhouse-Geiser correction was employed if sphericity was violated. If a significant group × time interaction was observed, follow-up one-way ANOVAs and paired-samples *t*-tests were used to explore the differences.

## **Results**

For both dependent variables, no violations of Mauchly's test of sphericity ($p$>0.30) were observed, so no corrections were employed. Normality was also assessed and found to be normally distributed (e.g., skewness and kurtosis statistics were < +/- 1 for all scales).

There was a significant group × time interaction for knee flexion at landing, $F(2,116)=54.89$, $p<0.001$, $\eta_p^2=0.486$. Follow-up paired sample *t*-tests showed a significant change (i.e., more flexion) in knee flexion at landing from pre-test to post-test for the OPTIMAL group ($p<0.001$). At retention, knee flexion was still lower than pre-test ($p<0.001$) for the OPTIMAL group. There was no change in knee flexion across the three time points for the control group (all $p>.05$). Means and standard deviations are presented in Table 2.

Table 2. Knee Flexion Angle (deg) comparing Day 1 to Day 2. All variables represented as Mean (SD). Asterisks (*) represent significant within-group findings from pre/post-test and pre/retention test.

| **Group** | **Knee Flexion Angle Pre-Test: Landing** | **Knee Flexion Angle Post-Test: Landing** | **Knee Flexion Angle Retention: Landing** |
|---|---|---|---|
| *Control* | 102.85 (9.68) | 103.03 (9.95) | 103.39 (10.01) |
| *OPTIMAL* | 107.62 (12.97) | 95.91 (9.24)* | 98.80 (9.32)* |

There was a significant group × time interaction for hip-knee alignment $F(2,116)=44.84$, $p<0.001$, $\eta_p^2=0.481$. Follow-up paired sample *t*-tests showed a significant increase in hip-knee alignment at landing from pre-test to post-test for the OPTIMAL group ($p=0.003$). At retention, hip-knee alignment was still more aligned than at pre-test ($p<0.001$). Means and standard deviations can be seen in Table 3.

Table 3. Hip-knee alignment (HKA in %) comparing Day 1 to Day 2. All variables represented as Mean (SD). Asterisks (*) represent significant within group findings from pre/post and pre/retention.

| **Group** | **HKA: Rebounding Pre-Test** | **HKA: Rebounding Post-Test** | **HKA: Rebounding Retention** |
|---|---|---|---|
| *Control* | 24.8 (13.1) | 24.7 (12.6) | 25.2 (13.1) |
| *OPTIMAL* | 28.4 (12.6) | 8.2 (9.3)* | 12.5 (8.9)* |

## Discussion

The purpose of this study was to examine the extent to which OPTIMAL Theory may enhance neuromechanical characteristics relative to ACL injury risk in a dynamic and sport specific task of basketball rebounding. Specifically, we examined knee flexion angle and hip-knee alignment when landing from the jump after rebounding a basketball during one day of instruction, and we tested retention 24 hours later. Our hypothesis was supported through the observation that the OPTIMAL Theory group exhibited lower extremity neuromechanics that reflect reduced ACL injury risk. Furthermore, these enhanced neuromechanics were retained 24 hours later, suggesting that a relatively short practice session (25 trials) with OPTIMAL Theory-based instructions led to learning motor patterns that were retained one day later.

Our findings replicate and extend support for OPTIMAL Theory relative to learning and retaining motor skills. A unique contribution of this study is that it is the first to examine this theory in the context of lower extremity neuromechanics that are related to ACL injury. Previous work examining this theory focused on upper extremity tasks, such as dart throwing (Wehlmann et al., 2020), lassoing (Wulf et al., 2018), bag toss (Wulf et al., 2018), and bowling (Abdollahipour et al., 2019). Our data replicated previous work by showing that combining the three elements of OPTIMAL theory can enhance motor control and learning. Moreover, we extended these findings by utilizing a lower extremity dynamic and sport-specific task. Such an approach lays the foundation for the adoption of OPTIMAL theory in more applied settings.

The findings of this study build upon our previous work showing that hip-knee alignment in a box squat and depth drop can be improved when using OPTIMAL Theory (Pierson et al., 2019, 2020). The current study was the next logical extension of that work that scaled up the task to the more dynamic and sport-specific task of basketball rebounding. It is well known from the literature that knee flexion and hip-knee alignment at landing are ACL injury risk factors due to their association with forces that are dissipated by the knee ligaments (Hron et la., 2020; Leppänen et al., 2017; García et al., 2020). With this context in mind, our central question in this study was focused on the extent to which OPTIMAL theory may positively alter knee flexion and hip-knee alignment at landing, thus potentially decreasing ACL injury risk.

Deeper knee flexion at landing has been shown to reduce injury risk by allowing more time to dissipate the vertical ground reaction force, ultimately leading to a lower moment of force on the ACL (Hron et la., 2020; Leppänen et al., 2017). Enhanced knee flexion at landing has been previously accomplished via ACL IPPs (Leppänen et al., 2017; García et al., 2020). The uniqueness of our study is the relatively small-time investment that was required to increase knee flexion at landing (25 practice trials). This shows that the components of OPTIMAL theory can alter behavior on a relatively short time scale.

Hip-knee alignment was the other variable of interest in this study. As one loads the knees and hips, the knees tend to come closer, creating a valgus moment. There is disagreement within the field about excessive knee valgus leading to ACL injury (Quatman et al., 2009; Hashemi et al., 2011; Markolf et al., 1995; Yu & Garrett, 2007; Yeow et al., 2008). Regardless, from a performance standpoint, knee valgus it is not advantageous because proper alignment (i.e., limiting valgus) aids more power and strength (Monfort et al., 2019). Keeping proper body alignment (i.e., hips, knees, and ankles in similar planes of motion) can increase sports performance and potentially reduce injury risk (Ludwig et al., 2017; Saki et al., 2019; Garcia-Luna et al., 2020). As seen in our study's results, the OPTIMAL group was able to learn and retain more advantageous movement in a dynamic task. Both knee flexion and hip-knee alignment were able to be altered in a short period of time, potentially influencing the risk of injury.

An important aspect of this study was the retention testing. Retention of a motor skill shows learning and neuromotor reorganization may have occurred. Some previous OPTIMAL Theory studies have also used the 24-hour retention testing (Abdollahipour et al., 2019; Chua et al., 2020), while others have not implemented a retention test (Lemos et al., 2017; Abdollahipour et al., 2019; Chua t al., 2020; Simpons et al., 2020). Our study was the first to examine OPTIMAL Theory with the lower extremity while also including retention testing. Our data show that the OPTIMAL Theory group retained what they had learned 24 hours later, supporting previous OPTIMAL studies that included retention testing (Wulf et al., 2016; Wulf et al., 2018). While this study only examined a short learning and retention window, these data suggest that OPTIMAL theory may be viable in more dynamic and sport-specific settings.

As with any study, there are limitations. One limitation was that these data were collected during the COVID-19 pandemic. Therefore, the participants and researcher were required to wear facial coverings. However, to our knowledge, this did not negatively affect our data collection or the participant's ability to learn. Another limitation was that the participant population was relatively young and healthy. We do not yet know, or have data to support, how OPTIMAL Theory affects those outside this range. Lastly, only a 24-hour retention window was included.

In conclusion, this study showed that OPTIMAL Theory can have a positive impact on lower extremity movements that reflect ACL injury risk. Future work should focus on more extended retention durations, along with a more diverse participant population and more sport specific tasks.

CHAPTER V

MANUSCRIPT II: TRANSFER OCCURS IN A DYNAMIC TASK USING OPTIMAL THEORY

## Introduction

The anterior cruciate ligament (ACL), a ligament in the knee that helps stabilize the joint, can cause significant challenges if injured. Women and girls sustain ACL injuries at higher rates than men and boys (Agel et al., 2016). Injuring the ACL can be costly in many aspects, including monetary, social, and economic. For athletes, an ACL injury accounts for the most lost time in sport relative to all other tracked injuries (Mueller & Casa, 2011). The amount of time out of sport for an ACL injury ranges from nine months to two years (Capin et al, 2019). To help reduce the impact and prevalence of this issue, ACL injury prevention programs (IPPs) have been developed that focus on enhancing neuromechanical variables known to relate to ACL injury risk.

While ACL IPPs have shown some success at reducing injury rates (Webster et al., 2018; Taylor et al., 2015; Sugimoto et al., 2012), they have not had the magnitude of impact desired by the athletic and sports medicine community. One area of refinement could be the infusion of more recent theory from motor learning that has not yet been implemented into these programs. Namely, an external focus of attention has over 20 years of laboratory and field-based experiments showing that focusing on the outcome of the task rather than the body part or body movement is beneficial in motor learning and retention (Wulf, 2013; Chua et al., 2019; Kuhn et al., 2017; Mornell et al., 2019) More recently EF has been combined with the motivation concepts of autonomy of support (AS) and enhanced expectancies (EE). AS provides the participant with a sense of control by allowing them to ask questions or request feedback throughout the task, which has been shown to enhance motor learning (Wulf et al., 2015). EE provides the participant with the sense that they are performing above average on the task, even if they are not (McKay et al., 2012), which has also been shown to be beneficial in the motor learning process (Wulf, 2013). Collectively, EF, AS, and EE have been combined under a single umbrella named Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) Theory (Wulf & Lewthwaite, 2016).

Adopting the three components of OPTIMAL Theory has been shown to enhance motor learning in upper limb tasks (Kim et al., 2017; Bahmani et al., 2018; Levac et al., 2019). Our previous work extended this line of research to show that OPTIMAL Theory is also beneficial when learning to enhance hip-knee alignment in a relatively static lower extremity task (i.e., box squat) (Pierson, 2019), and that enhanced alignment was transferred to a depth drop (Pierson et al., 2020). We have also recently shown that the OPTIMAL Theory is beneficial at enhancing knee flexion and hip-knee alignment in a dynamic and sport-specific task of basketball rebounding (Pierson et al., in development). The next logical question in this line research is the extent to which practicing rebounding with OPTIMAL Theory instructions may transfer to a similar dynamic lower extremity task. This aligns with the observation that the concept of transfer has not been widely investigated in ACL IPPs. We describe transfer as the ability to learn one movement or task and be able to apply it to another similar, yet different task. This could be impactful for ACL IPPs, as learning correct movement patterns in one task could lead to a similar benefit in other tasks. For example, learning proper squat mechanics could transfer to landing from a jump with proper mechanics. These tasks are different but have similar movement patterns. This could be impactful for ACL IPPs, as there are movements performed in an ACL IPP, but there is no feasible way to perform every movement an athlete would perform in a competitive setting. Better understanding learning transfer and retaining the newly learned movement patterns could lead to decreased injury in athletic populations. However, prior to adopting OPTIMAL Theory in ACL IPPs, it is important to first establish its utility to alter lower extremity mechanics in transfer tasks relative to known ACL risk factors (e.g., knee flexion and hip-knee alignment).

The purpose of this study was to examine the extent to which lower extremity neuromechanics are altered on a transfer task (i.e., vertical jump landing) after implementing OPTIMAL Theory in a basketball rebounding practice session. We hypothesized that compared to the control group, the OPTIMAL Theory group would have increased knee flexion and enhanced hip-knee alignment on the vertical jump landing after the practice session of basketball rebounding, and that these movement patterns in the OPTIMAL group would be retained during testing the following day.

## Methods

### Participants

A total of 60 young healthy adults from the University of North Carolina at Greensboro in Greensboro, North Carolina were recruited for this study. Participants were randomly assigned to the OPTIMAL (n=30) or control group (n=30). All participants were between the age of 18-35 years old. All participants were screened for COVID-19 symptoms and eligibility based on inclusion and exclusion criteria. Criteria for exclusion were: (1) positive test for COVID-19; (2) previous injury to the lower extremity that altered their daily life in the past six months; (3) any current musculoskeletal injuries or impairments that lead to pain or discomfort while running and jumping; (4) surgery to the knee in the last 12 months; (5) lack of sports participation in basketball, volleyball, football or soccer for a minimum of three years.

Table 4. Participant Demographics. All variables represented as Mean (SD).

| **Group** | **Age (years)** | **Height (cm)** | **Weight (kg)** | **Sex** |
|---|---|---|---|---|
| *Control* | 22.1 (3.3) | 167.9 (9.7) | 71.6 (16.1) | F=20; Male = 10 |
| *OPTIMAL* | 21 (3.6) | 172.2 (10.9) | 81.0 (22.8) | F=15; Male=15 |

### Experimental Design

A schematic of the study design is presented in Figure 4. This was a 2-day study which collected pre-test and post-test data on Day 1. Retention data were collected after a 24-hours later. Pre-test, post-test, and retention testing included a simulated basketball rebound and maximal effort vertical jump. Two cameras (GoPro Hero5, San Mateo, CA)—one in front and one on the participant's right side) were used to record lower extremity motion that was later processed using Kinova software to obtain knee flexion angles (sagittal plane) and hip-knee alignment (frontal plane).

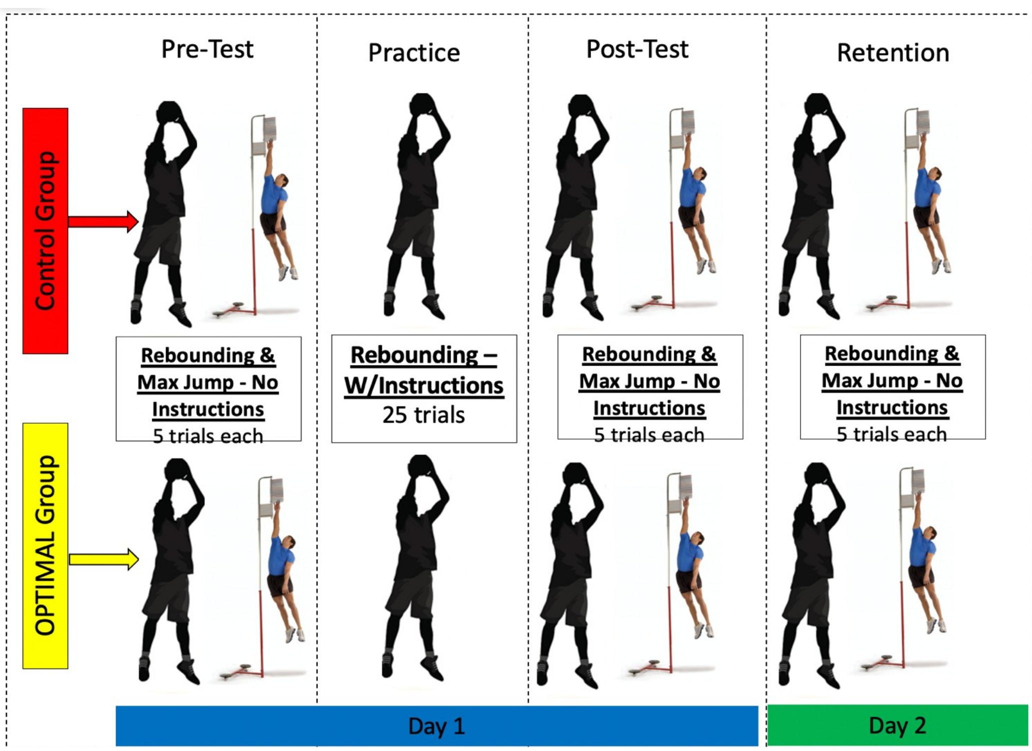


Figure 4. Experimental Design.

## Experimental Procedure

### ***Day 1***

Participants were tested in a research gymnasium to best simulate sport specific movements. Within the gym, demographic information was collected, and height, weight, and hip width were measured. A researcher then marked an "X" on the center of the patella of the participant to aid in tracking the participant's movement when processing and also to use the mark as a reference during instructions. Next, a researcher led each participant through a dynamic warm-up, after which pre-testing began that included five basketball rebounds with no instructions other than "*Catch the ball at the highest point possible to mimic a rebound*." The next task for pre-testing was the maximal effort vertical jump, performed on the VerTec. Subjects in both groups were instructed to, "*Jump as high as possible, to reaching the highest rung*." After pre-testing and a five-minute break, participants moved to the practice block on the study design.

During the practice block, participants performed 25 basketball rebounds using a five rebounds, break, five rebounds, break, etc. structure. During this practice block, participants' instructions varied based on group assignment. The OPTIMAL theory group's instructions were *"Jump like a spring and catch the ball at the highest part of the jump. While doing that try to keep the "X's" in alignment [EF component]. You can ask me for feedback at any point during your trials [AS component]. You are doing much better than the previous subject [EE component]"*. The control group was only instructed to "Jump and catch the ball at the highest possible point to mimic a rebound….” Instruction was given at the start of each five-rebound practice set. After each five-rebound set, the OPTIMAL group was shown their video of their previous practice round on the tablet. The subject could only view his/her hip-knee alignment, all else was blocked. Both groups received 3 minutes of rest. For the OPTIMAL group, assessing their own hip-knee alignment was part of the external focus of attention component, as subjects were instructed to focus on the “X’s” and to try and keep them in alignment compared to their hips. After the 25-rebound practice block and a break, post-testing began. Post-testing mirrored pre-testing, which was 5 basketball rebounds with no instruction other than “*Catch the ball at the highest point possible to mimic a rebound*.”. After a 5-minute break, the maximal effort vertical jump was tested. This occurred the same way as it did during the pre-test with five jumps and the same instructions.

### *Day 2*

After a 24-hour period, participants returned to the research gymnasium. They completed the same warm-up that was performed on Day 1, followed by retention testing that included 5 basketball rebounds and five maximal vertical jumps. No performance instructions were given to either group for either task on Day 2 other than “*Complete the task as you remember from yesterday*”. Cameras were used to capture both frontal and sagittal planes of movement, identical to Day 1.

## Data Reduction

Video from the cameras were uploaded to Kinovea (version 2.2.0), a free 2D motion analysis software for which the validity and reliability has been previously reported (Puig-Divi et al., 2019; Balsalobre-Fernández et al., 2014). For both tasks, knee flexion angles in the sagittal plane and knee-hip alignment in the frontal plane were computed via the Kinovea software by identifying landmarks on the lower limb previously marked (i.e., malleolus, lateral epicondyle, and greater trochanter). For the purposes of this paper, knee flexion was defined as the angle of the knee during the lowest point of the vertical jump landing between the femur and tibia. Hip-knee alignment was defined as the extent to which the knees were aligned with the hips at the lowest point of the vertical jump landing. Hip-knee alignment is presented as a ratio and calculated via the following equation:

$$\frac{Hip\ width\ distance\ -\ Knee\ separation\ distance}{Hip\ Width\ Distance}\ X\ 100\ =\ Hip\ -\ Knee\ Alignment$$

Hip width distance was measured in cm from anterior superior iliac crest on both sides across the pelvis, and knee separation distance was measured in cm from the center of the patella. Hip width distance and knee separation distance were both measured in the frontal plane. For hip-knee alignment, a value of 0% represents perfect alignment, whereas values greater than that represent the magnitude of misalignment. Since only magnitude of alignment was of interest, the absolute value of this ratio is reported.

All videos for this study were processed by the same person. Only videos from the rebounds during the pre-test, post-test, and retention test were analyzed. Averages were computed within each block. For example, the 5 pre-test jumps for a participant were converted into one singular average which represents their entire pre-test. The same was done for post-test and retention test.

## **Statistical Analysis**

A 2 (group) × 3 (time period) repeated measures ANOVA was used examining changes in knee flexion and hip-knee alignment while landing from the vertical jump across the pre-test, post-test, and retention test. Alpha level was set to a priori at 0.05. To reduce type I error, Mauchly's test of sphericity was used and a Greenhouse-Geiser correction was employed if sphericity was violated. If a significant group × time interaction was observed, follow-up one-way ANOVAs and paired-samples t-tests were used to explore the differences.

## **Results**

For both dependent variables, no violations of Mauchly's test of sphericity ($p$>0.50) were observed, so no corrections were employed. Normality was also assessed and found to be normally distributed (e.g., skewness and kurtosis statistics were < +/- 1 for all scales).

There was a significant group × time interaction for knee flexion at landing during the maximal effort vertical task, $F(2,116)=54.78$, $p<0.001$, $\eta_p^2=0.486$.

Follow-up paired sample *t*-tests showed a significant change (i.e., more flexion) in knee flexion at landing from pre-test to post-test for the OPTIMAL group ($p<0.001$).

At retention, knee flexion was still lower than pre-test ($p<0.001$) for the OPTIMAL group. There was no change in knee flexion from pre-test to post-test to retention test for the control group (all $p>.05$). Means and standard deviations are presented in Table 5.

Table 5. Landing Knee Flexion Angles Between Pre-test, Post-test and Retention test for Maximal Effort Vertical Jump. All variables represented as Mean (SD). Asterisks (*) represent significant within-group findings from pre/post and pre/retention.

| **Group** | **Pre-Test -Landing: Max Jump** | **Post-Test – Landing: Max Jump** | **Retention-Test – Landing: Max Jump** |
|---|---|---|---|
| *Control* | 100.74 (8.48) | 100.83 (9.26) | 100.83 (9.02) |
| *OPTIMAL* | 100.59 (9.00) | 90.65 (5.13)* | 91.86 (8.53)* |

Table 6. Hip-Knee Alignment (HKA) Pre-test, Post-test and Retention test for Maximal Effort Vertical Jump. All variables represented as Mean (SD). Asterisks (*) represent significant within-group findings from pre/post and pre/retention.

| **Group** | **Pre-Test -HKA: Max Jump** | **Post-Test – HKA: Max Jump** | **Retention-Test – HKA: Max Jump** |
|---|---|---|---|
| *Control* | 34.9 (11.1) | 32.1 (14.4) | 31.8 (13.1) |
| *OPTIMAL* | 36.6 (13.7) | 10.1 (11.2)* | 17.0 (9.8)* |

There was a significant group × time interaction for hip-knee alignment, $F(2,116)=36.50, p<0.001$, $\eta_p^2=0.386$. Follow-up paired sample *t*-tests showed a significant increase in hip-knee alignment at landing from pre-test to post-test for the OPTIMAL group ($p=0.017$). At retention, hip-knee alignment was still more aligned than at pre-test ($p<0.007$). There was no change in knee flexion from pre-test to post-test to retention test for the control group (all $p>.05$). Means and standard deviations can be seen in Table 6.

## Discussion

The purpose of this study was to examine the extent to which lower extremity neuromechanics are altered on a transfer task (i.e., vertical jump landing) after implementing OPTIMAL Theory in a basketball rebounding practice session. Specifically, we examined knee flexion and hip-knee alignment after landing from the maximum vertical jump before and after 25 practice trials of basketball rebounding on day 1. We also tested retention 24-hours later. Our hypothesis was supported through the observation that the OPTIMAL Theory group exhibited lower extremity neuromechanics that reflect reduced ACL injury risk in the transfer test, congruent with our findings on the original basketball rebounding lower extremity neuromechanics (Pierson et al., in development). Furthermore, these enhanced neuromechanics in the transfer test were retained 24 hours later, suggesting that OPTIMAL Theory-based instructions in a relatively short practice session can lead to the transfer to motor skills to a similar, yet different dynamic task.

Our findings are congruent with a previous OPTIMAL Theory through the observation that the OPTIMAL group outperformed other groups in a retention test (Wulf et al., 2013; Chua et al., 2019). Our findings extend and add to this body of work as we utilized a control group and a transfer task. We also extended beyond this original study as we used dynamic movement, evaluating lower body mechanics. Most OPTIMAL Theory studies to date have used upper extremity tasks (Abdollahipour et al., 2019; Wulf et al., 2018a; Wulf et al., 2018b; Wulf et al., 2017), whereas our study used a lower extremity task as the intervention and lower extremity transfer task. Our data show that OPTIMAL Theory group transferred their lower ACL injury risk mechanics to a new landing task, suggesting this type of instruction may be a viable candidate for inclusion in ACL IPPs. To date, only external focus of attention has been applied thus far to ACL IPPs (Benjaminse et al. 2015; Benjaminse et al. 2018; Gokeler et al., 2013; Gokeler et al., 2015; Gokeler et al., 2018; Gokeler et al., 2019).

Knee flexion has been of interest in ACL IPPs because it is known that more knee flexion leads to lower vertical ground reaction peak forces (Padua et al., 2009; Blackburn et al., 2013; Myer et al., 2011). Encouraging a more flexed knee in landing tasks is an important component of many ACL IPPs (Padua et al., 2009; Nessler et al., 2017), as many ACL injuries occur when coming down from a land (Boden et al., 2000). When an athlete lands too stiff (i.e., little knee flexion), there is a very high peak vertical ground reaction force that must be dissipated by the knee ligaments. Teaching the athlete to adopt a more flexed knee (i.e., softer landing) is a primary goal of ACL IPPs. Other studies have shown success in teaching landing mechanics to decrease vertical ground reaction forces and encourage a more flexed knee at landing (Noyes et al., 2012; Sugimoto et al., 2015). However, this is typically done in a controlled laboratory setting with no sport application. Our study's results show that it is possible to adopt lower extremity mechanics in a transfer task that align with less ACL injury risk in a relatively short practice session using OPTIMAL Theory instructions. This study adds to the small body of work investigating how to teach a softer landing.

Hip-knee alignment is a controversial risk factor for ACL injury. Some believe that limiting knee valgus and creating more alignment in between the hips and knees will reduce the risk for ACL injury (Hewett et al., 2005). However, some have shown that limiting knee valgus and knee to hip alignment does not negate the risk of ACL injury (Yu et al., 2007). Nevertheless, ACL IPPs have been using this as a risk factor from the beginning and structure many of its framework around limiting poor hip-knee alignment. Previous studies have shown success at improving alignment between the hip and knee (Hewett et al., 2005; McClean et al., 2005; Numata et al., 2018). Our study adds to the literature by using a transfer task and showing transfer of hip-knee alignment between tasks was possible. Better lower body alignment is also important from a performance aspect. Replicating mechanics with better alignment can aid performance aspects, such as jump performance (McCormack et al., 2021; Ikeda et al., 2021; Simmermann et al., 2018; Daugherty et al., 2021).

Testing transfer and retention, especially in dynamic movement, is an important contribution of the current study. As our previous and current work has shown, the OPTIMAL group retained safer mechanics on both the main task (rebounding) (Pierson et al., in development) and the transfer task (maximal effort vertical jump in the current study). Limited research has tested the ability of transfer in the lower extremity. However, transfer is a goal of most ACL IPPs and rehabilitation programs. Transferring the more advantageous movement to similar movements, without having to practice them repetitively, establishes the learned movement. As observed in our study, the OTPIMAL group was able to retain better movement mechanics (hip-knee alignment and knee flexion) on the transfer task. No group received instructions on the transfer task, but the OTPIMAL group was able to transfer safer mechanics from the rebounding task. From an injury prevention standpoint, learning safer mechanics of movement and successfully transferring them to other similar tasks likely equates to a decrease in injury risk. While the area of transfer in dynamic, sport-related movements has limited research, the successful application of transfer could alter ACL IPPs in how they are structured.

As with most studies, there were some limitations. This study was only a two-day study. Further investigation for longer durations would be advantageous to see the full effects of OPTIMAL Theory and its capacity. Another limitation would be that instructions were given by the PI with a facemask and face shield on due to the following COVID guidelines. Participants were also wearing a facemask.

While our results do not indicate that this lessened our delivery, limiting the part of the typical human interaction with facial expression may be a limitation. If face coverings are worn in future applications, special attention should be made to ensure proper and effective delivery of instructions.

In conclusion, this study showed that a group who was provided OPTIMAL Theory instructions on a basketball rebound transferred their newly adopted lower extremity mechanics to the similar task of landing from a maximum vertical jump with respect to increased knee flexion and enhanced hip-knee alignment. This study holds important applications for ACL IPPs and injury reduction.

# CHAPTER VI

# MANUSCRIPT III: EXAMING DYNAMIC TO STATIC RELATIONSHIP OF LEARNING AND TRANSFER IN THE LOWER EXTREMITY

## Introduction

There remains an empirical question in motor learning around the extent to which performance on static task may relate to dynamic task performance. An example of this is from the balance control literature, where static postural control tests have long been used to assess neuromotor control (Diener et al., 1984; Winter et al., 1998), but the question remains as to the extent to which performance on the static test extends to more functional and dynamic activities of daily living (Shubert et al., 2006). In their study of 195 community dwelling older adults, Shubert et al. (2006) found that static and dynamic balance were moderately associated. However, the directionality of the transfer of performance has not yet been examined. That is, is balance control a generalized skill that would lead to similar performance in both static and dynamic tasks, or if a balance skill is learned in one context, does it extend to the other?

One area where balance control is emphasized is in training programs that are designed to reduce injury risk. An example of this is in anterior cruciate ligament (ACL) injury prevention programs (IPPs). The ACL, a stabilizing ligament in the knee, is often injured during landing, cutting or jumping. In an ACL IPP, progressions occur from static to dynamic balance control, with the goal of teaching the performer to exhibit landing mechanics in the lower extremity that are known to reduce injury risk, such as increased knee flexion and hip-knee alignment (Norcross et al., 2016). While ACL IPPs have shown some success at reducing injury rates (Webster et al., 2018; Taylor et al., 2015; Sugimoto et al., 2012), they have not had the magnitude of impact desired by the athletic and sports medicine community. There is room to refine these programs through the infusion of

Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) Theory, a relatively new theory in motor learning. OPTIMAL Theory is comprised of three separate components that have all shown success in learning and retention (Abdollahipour et al., 2019; Wulf et al., 2018b, Wulf, 2013; Chua et al., 2019; Kuhn et al., 2017; Mornell et al., 2019; Wulf et al., 2015; McKay et al., 2012; Wulf & Lewthwaite, 2016). This includes: (1) external focus of attention, (2) autonomy of support, and (3) enhanced expectancies. An external focus of attention (EF) is focusing on the outcome of the task rather than the body part or body movement (Wulf, 2013; Chua et al., 2019; Kuhn et al., 2017; Mornell et al., 2019). Autonomy of support (AS) provides the participant with a sense of control by allowing them to ask questions or request feedback throughout the task (Wulf et al., 2015). Enhanced expectancies (EE) provide the participant with the sense that they are preforming above average on the task, even if they are not (McKay et al., 2012; Wulf, 2013). The combination of these components has been evaluated in the upper extremity with relatively stationary tasks (Lemos et al., 2017; Ghorbani et al., 2019; Diekfuss et al.,2021; Diekfuss et al., 2020; Chua et al., 2018; Singh et al. 2020) and our previous work examined the utility of OPTIMAL Theory in lower extremity tasks (Pierson et al., 2019, 2020, Pierson et al., in development).

Our original work in this space examined OPTIMAL Theory in the relatively stationary lower extremity task of a box squat to examine hip-knee alignment before and after instruction. The results showed that the OPTIMAL Theory group exhibited enhanced hip-knee alignment after a practice session (Pierson et al., 2019), and that enhanced alignment was transferred to a depth drop (Pierson et al., 2020). Our next study extended this work by implementing OPTIMAL Theory in a more dynamic and sport-based task of basketball rebounding. Similar to our original study, we showed the OPTIMAL Theory group exhibited enhanced hip-knee alignment and greater knee flexion (both indicators of reduced ACL injury risk) when landing from a basketball rebound (Pierson et al., in development), and those mechanics were transferred to the similar dynamic skill of landing from a maximum vertical jump (Pierson et al., in development). Now that we have demonstrated that OPTIMAL Theory can positively alter lower extremity mechanics (and therefore balance), and those mechanics are transferred to a similar skill, a key question from a motor learning perspective is the extent to which these newly learned balance skills are exhibited in a wider range of skills, including static postural control. While continuing to explore progressively more dynamic tasks is logical, examining the extent to which transfer of performance in static tasks exists could be relevant from both a basic and clinical science perspective. From a basic science lens, this would help address the question of whether balance is a generalized or context-dependent skill. From a clinical science perspective, it would be valuable if performance on a dynamic task (especially from an injury risk perspective) could be gleaned from rather simple static task. Utilizing a static balance task, such as the Balance Error Scoring System (BESS) test (Riemann et al., 1999; Riemann et al., 2000) is an easy, cost-effective, and subjective way to examine postural control. Utilizing a portable force plate while performing the BESS test provides an objective measurement to add to the subjective assessment (Alsalaheen et al., 2015).

The purpose of this study was to examine the extent to which enhanced performance learned during a dynamic task (i.e., a basketball rebound) via OPTIMAL Theory instructions transfer to a static balance control task. We hypothesized that the compared to the control group, the OPTIMAL Theory group would have decreased BESS error scores and decreased CoP after the practice session of basketball rebounding, and that these enhanced movement patterns in the OPTIMAL group would be retained during testing the following day.

## Methods

### Participants

A total of 60 young healthy adults from the University of North Carolina at Greensboro in Greensboro, North Carolina were recruited for this study.

Participants were randomly assigned to the OPTIMAL (n=30) or control group (n=30). All participants were between the age of 18-35 years old. All participants were screened for COVID-19 symptoms and eligibility based on inclusion and exclusion criteria. Criteria for exclusion were: (1) positive test for COVID-19; (2) previous injury to the lower extremity that altered their daily life in the past six months; (3) any current musculoskeletal injuries or impairments that lead to pain or discomfort while running and jumping; (4) surgery to the knee in the last 12 months; (5) lack of sports participation in basketball, volleyball, football or soccer for a minimum of three years.

Table 7. Participant Demographics. All variables represented as Mean (SD).

| **Group** | **Age (years)** | **Height (cm)** | **Weight (kg)** | **Sex** |
|---|---|---|---|---|
| *Control* | 22.1 (3.3) | 167.9 (9.7) | 71.6 (16.1) | F=20; Male = 10 |
| *OPTIMAL* | 21 (3.6) | 172.2 (10.9) | 81.0 (22.8) | F=15; Male=15 |

## Experimental Design

A schematic of the study design is presented in Figure 5. This was a 2-day study which collected pre-test and post-test data on Day 1. Retention data were collected after a 24-hours break. Pre-test, post-test, and retention testing included a simulated rebound and the BESS test. A single camera (GoPro Hero5, San Mateo, CA) in front of the participant was used to record the participant's movements that were later scored for the BESS test. All video was scored by the same person using the established rubric.

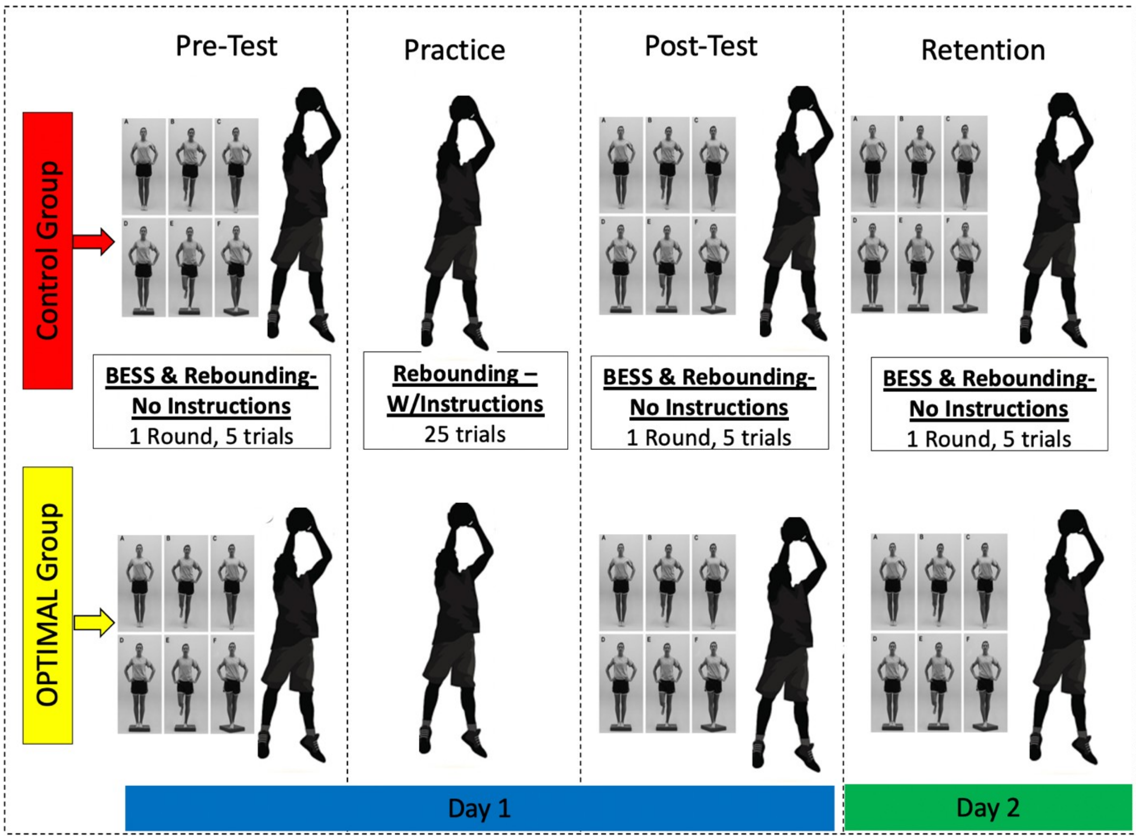


Figure 5. Experimental Design.

## Experimental Procedure

### *Day 1*

Participants were tested in a research gymnasium to best simulate sport specific movements. Within the gym, demographic information was collected, and height, weight, and hip width were measured. A researcher then marked an "X" on the center of the patella of the participant to aid in tracking the participant's movement when processing and also to use the mark as a reference during instructions. Next, a researcher led each participant through a dynamic warm-up, after which pre-testing began that included the BESS test. Participants were instructed per the BESS script (Appendix B) which was basic task instructions for the different positions. All BESS testing took place on the BTrackS portable force plate (BTrackS, Balance Tracking System Inc. San Diego, CA, USA). Then participants went to their next pre-test, which consisted of five basketball rebounds. For the pre-test, no instructions other than "*Catch the ball at the highest point possible to mimic a rebound*" were given. After pre-testing and a five-minute break, participants moved to the practice block on the study design.

During the practice block, participants performed 25 basketball rebounds using five rebounds, break, five rebounds, break, etc. structure. During this practice block, participants' instructions varied based on group assignment. The OPTIMAL theory group's instructions were *"Jump like a spring and catch the ball at the highest part of the jump. While doing that try to keep the "X's" in alignment [EF component]. You can ask me for feedback at any point during your trials [AS component]. You are doing much better than the previous subject [EE component]"*. The control group was only instructed "*Jump and catch the ball at the highest possible point to mimic a rebound.*." Instruction was given at the start of each five-rebound practice set. After each five-rebound set, the OPTIMAL group was shown their video of their previous practice round on the tablet. The subject could only view his/her hip-knee alignment; all else was blocked. Both groups received 3 minutes of rest. For the OPTIMAL group, assessing their own hip-knee alignment was part of the external focus of attention component, as subjects were instructed to focus on the “X’s” and to try and keep them in alignment compared to their hips. After the 25-rebound practice block and a break, post-testing began. Post-testing mirrored pre-testing, which was 5 basketball rebounds with no instruction other than “*Catch the ball at the highest point possible to mimic a rebound*.”. After a 5-minute break, the BESS testing occurred. This occurred the same way as it did during the pre-test with the same basic task instructions.

### ***Day 2***

After a 24-hour period, participants returned to the research gymnasium. They completed same warm-up that was performed on Day 1, followed by retention testing that included the BESS test and 5 basketball rebounds. No performance instructions were given to either group for either task on Day 2 other than “*Complete the task as you remember from yesterday*”. Cameras were used to capture the frontal view for BESS testing, identical to Day 1.

## **Data Reduction**

For BESS testing, the rubric was used. An error counted when the subject 1) moved their hands off their iliac crests, 2) opened their eyes, 3) stepped or stumbled or fell, 4) abducted or flexed their hip beyond 30 degrees, lifted the forefoot or heel off the testing surface, and 5) remained out of the proper testing position for more than 5 seconds. All the error scores were summed from all six conditions for our analysis. All video was downloaded and scored by the same person.

Center of Pressure (CoP) score was taken from the BTrackS software program, at which the BESS Test took place. CoP path length (cm) was summed across the six BESS conditions, resulting in a total path length value. The CoP is a proxy for postural-sway magnitude, so larger path length values are indicative of greater postural sway or less balance control. The path length was determined by in a multistep process. To quantify the point-to-point path length between successive time points, the following equation was used

$$(\{COP_{x2} - COP_{X1})^2 + \{COP_{y2} - COP_{y1}\}^2)^{.05}$$

with $COP_{x2} - COP_{X1}$ representing the adjacent time points in $COP_x$ (medial-lateral) time series and $COP_{y2} - COP_{y1}$ representing the anterior posterior time series.

## Statistical Analysis

For both dependent variables (BESS score and CoP path length), separate 2 (group) × 3 (time period) repeated measures ANOVAs were used examining changes across the pre-test, post-test, and retention test. Alpha level was set to a priori at 0.05. A Greenhouse-Geiser correction was used for non-normally distributed data. If significant group by time interactions occurred, a one-way ANOVA was used to determine which group shows differences and a paired samples t-test will then be used to determine at which point there are significant differences.

## Results

For both dependent variables, no violations of Mauchly's test of sphericity ($p$>0.71) were observed, so no corrections were employed. Normality was also assessed and found to be normally distributed (e.g., skewness and kurtosis statistics were < +/- 1 for all scales).

For the BESS test, neither the interaction, $F(2,116)=0.003$, $p=0.997$, $\eta_p^2=0.002$ nor the main effect of group $F(2,116)=0.113$, $p=0.893$, $\eta_p^2=<0.001$ were significant. For path length, the interaction was not significant $F(2,116)=0.306$, $p=0.737$, $\eta_p^2=0.005$ , but there was a significant main effect of time $F(2,116)=4.89$, $p=0.009$, $\eta_p^2=0.078$. Data for the BESS test and for COP are presented in Tables 8 and 9.

Table 8. BESS Error Scores Average Total by Testing Time. All variables represented as Mean (SD).

| **Group** | **Pre-Test** | **Post-Test** | **Retention Test** |
|---|---|---|---|
| *Control* | 13.83 (5.82) | 14.1 (6.05) | 14.24 (5.40) |
| *OPTIMAL* | 14.90 (5.56) | 14.74 (5.51) | 15.26 (4.59) |

Table 9. CoP Displacement Average Total by Testing Time. All variables represented as Mean (SD).

| Group | Pre-Test | Post-Test | Retention Test |
|---|---|---|---|
| *Control* | 180.07 (46.54) | 175.75 (40.13) | 168.69 (44.56) |
| *OPTIMAL* | 173.83 (45.17) | 164.02 (34.44) | 161.64 (38.09) |

## Discussion

The purpose of this study was to examine the extent to which enhanced performance learned during a dynamic task (i.e., a basketball rebound) via OPTIMAL Theory instructions transfer to a static balance control task. We hypothesized that compared to the control group, the OPTIMAL Theory group would have decreased BESS error scores and decreased CoP after the practice session of basketball rebounding, and that these enhanced movement patterns in the OPTIMAL group would be retained during testing the following day.

Overall, our hypotheses were not supported. We observed a main effect for time for path length, indicating that participants enhanced their postural control from the pre-test to the retention test, but this enhancement was not dependent on group. This suggests the presence of a learning effect irrespective of task instructions. We observed no significant interaction or main effects for the BESS test, further supporting the lack of transfer from the basketball rebounding task to the static balance test.

To date, there are no studies that examine dynamic-to-static transfer in the lower extremity. Research typically examines learning movement in a natural progression from static to dynamic, and rarely from dynamic to static (Davids et al., 2012; Lackner et al., 2005). When this reverse natural progression is examined, it has been in the upper extremity (Lackner et al., 2005). Lackner (2005) investigated this reverse natural progression, but found little transfer occurring and reported a decrease in the accuracy of upper limb touch task. Our study extends the work by Lackner et al. (2005) by examining lower extremity movements in the dynamic-to-static transfer context. Better understanding how dynamic movements are learned and potentially transferred to static postural control has the potential of addressing the question of whether balance is a generalized or context-dependent skill. Our findings support the postulate that context is important in skill development (Ruitenbury et al., 2012; Krakauer et al., 2006)), at least when attempting to transfer performance on two rather disparate tasks. There would be clinical utility if skill performance on a static task reflected performance on a dynamic task, as the simpler static balance task could be used to screen for injury risk. Based on our findings, such an assumption cannot be supported. The dynamic-to-static transfer examined with this study may represent the boundary which performance transfer may not cross, as our previous work showed that the OPTIMAL Theory group transferred their enhanced performance in the basketball rebounding task to the similar dynamic task of a maximum vertical jump (Pierson et al., in development). The data presented in this paper suggest that the transfer does not extend to a more static task.

The BESS is a standard test used in many athletic settings (Bell et al., 2011). Since the test is used so widely, there are standards to evaluate scores to find normative values (Iverson et al., 2013; Iverson et al., 2008). The BESS test was designed to be a subjective test for clinical care that was validated against objective measurement via a force plate (Riemann et al., 1999). However, the subjectiveness of the BESS has raised questions about its utility (Finnoff et al., 2009). Administering the BESS on a portable force plate provides an objective measurement of postural control to be paired with the BESS subjective data (Alsalaheen et al., 2015). Nevertheless, the BESS is still a commonly used subjective measure of postural control (Brogilo et al., 2019). Our observation of no interactions for either BESS or CoP path length, and only a main effect of time for the CoP path length means one of two things. Either the subjectiveness of the BESS led to a lack of sensitivity to pick up on potential differences between groups or the enhanced performance of the OPTIMAL Theory group did not transfer to the static balance task. Combined with the observation that a group main effect or interaction for CoP path length was not observed, it is mostly likely the case that transfer did not occur between the dynamic and static tasks. While limited impactful findings occurred, this study added to the current literature. No studies have used CoP path length as a variable of interest when evaluating OPTIMAL Theory. Adopting this technique could help future OPTIMAL Theory studies quantity balance control differences between groups. This may ultimately lead to a better understanding how the learning process could transfer between different types of movements and may have application in sport, rehabilitation, and clinical settings. As with any study limitations occurred. This study was conducted during the COVID-19 pandemic, in which both participants and PI were required to wear facial coverings. While this did not affect other aspects of this study, it may have affected the instructional ability to be understood and/or applied since half the face was covered. This leaves little room for facial recognition and social cues to aid learning. Another limitation in this study was it tested a relatively young and healthy population. Results may vary based on differing population ages, previous or current illness, and previous experience with postural control.

In conclusion, we determined that using OPTIMAL Theory to enhance dynamic movement may not transfer to performance on a static balance task. These findings were supported using both subjective and objective balance assessment. However, further investigation is necessary to fully understand the capabilities of OPTIMAL Theory on balance control in a variety of tasks.

# CHAPTER VII

# EXECUTIVE SUMMARY

The purpose of this dissertation was to examine the extent to which OPTIMAL Theory could be applied to a lower extremity dynamic, sport-specific movement (i.e., basketball rebound) and the extent to which it may transfer to a similar dynamic and static task. Previous work in this space primarily examined OPTIMAL Theory using upper extremity tasks, making this dissertation a unique contribution to the literature. Our preliminary research examined OPTIMAL Theory in relatively static lower extremity movement (Pierson et al., 2020), and this dissertation extended that to a dynamic lower extremity movement. The findings of this dissertation support recent work showing that OPTIMAL Theory has a positive influence on motor learning and retention (Ghorbani et al., 2019; Diekfuss et al., 2021; Chua et al., 2018). Moreover, the potential of OPTIMAL Theory to be integrated into ACL IPPs was a major motivation of this dissertation. ACL IPPs have had limited success at reducing ACL injury rates. An area of refinement is the infusion of newer motor learning theories into ACL IPPs, namely OPTIMAL Theory. Intertwined in these questions was the extent to which retention and transfer would be observed within and between tasks when comparing an OPTIMAL Theory group to a control group. Therefore, these gaps were attended to with three purposes: (1) to compare performance of an OPTIMAL Training group to a control group in a jump/landing task of basketball rebounding, (2) is to compare the ability for transfer motor performance from the basketball rebounding task to a maximal effort vertical leap task and (3) to examine the extent to which enhanced performance learned during a dynamic task (i.e., a basketball rebound) via OPTIMAL Theory instructions transfer to a static balance control task.

In this dissertation, Manuscript 1 reports hip-knee alignment and knee flexion during the basketball rebound task. The OPTIMAL group received instructions containing enhanced expectancies, external focus of attention, and autonomy of support, whereas the control group received only task-based instructions. Compared to the control group, the OPTIMAL group showed deeper knee flexion and better alignment during the rebounding task from pre to post test. The OPTIMAL group was also able to retain the more advantageous movements the next day during retention testing. In Manuscript 2 we compared the extent to which transfer occurred between the basketball rebound and a maximum vertical jump, and showed that the OPTIMAL group again exhibited better hip-knee alignment and deeper knee flexion when landing in the transfer task. In Manuscript 3, we compared a different category of movement to our rebounding task, a static postural control task. We used a portable force plate to administer the BESS test. We found that transfer from dynamic movement to static postural control tasks did not occur.

As with any study, there were limitations. We collected this data during the COVID-19 pandemic. Therefore, the participants and researcher were required to wear facial coverings. However, to our knowledge, this did not negatively affect our data collection or the participant's ability to learn, retain and transfer. Another limitation was that the participant population was relatively young and healthy. We do not yet know, or have data to support, how OPTIMAL Theory affects those outside this range. Lastly, only a 24-hour retention window was included. Learning, retention and transfer beyond the 24-hour window is unknown at this time.

Future work should aim to test those outside the young and healthy range to find how learning, retention and transfer could be affected. Furthermore, retention past 24-hours should be examined to test if the learned movement patterns and transfer could be retained for longer durations. Despite the limitations of this study, this investigation shows a promising outlook for OPTIMAL Theory application in different fields of movement and learning.

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APPENDIX A

BESS TESTING PROTOCOLS

# Balance Error Scoring System (BESS)

*Developed by researchers and clinicians at the University of North Carolina's Sports Medicine Research Laboratory, Chapel Hill, NC 27599-8700*

The Balance Error Scoring System provides a portable, cost-effective, and objective method of assessing static postural stability. In the absence of expensive, sophisticated postural stability assessment tools, the BESS can be used to assess the effects of mild head injury on static postural stability. Information obtained from this clinical balance tool can be used to assist clinicians in making return to play decisions following mild head injury.

The BESS can be performed in nearly any environment and takes approximately 10 minutes to conduct.

**Materials**

Testing surfaces

-two testing surfaces are need to complete the BESS test: floor/ground and foam pad.

*1a) Floor/Ground:* Any level surface is appropriate.

*1b) Foam Pad* (Power Systems Airex Balance Pad 81000)

Dimensions: Length: 10" Width: 10" Height: 2.5"

The purpose of the foam pad is to create an unstable surface and a more challenging balance task, which varies by body weight. It has been hypothesized that as body weight increases the foam will deform to a greater degree around the foot. The heavier the person the more the foam will deform. As the foam deforms around the foot, there is an increase in support on the lateral surfaces of the foot. The increased contact area between the foot and foam has also been theorized to increase the tactile sense of the foot, also helping to increase postural stability. The increase in tactile sense will cause additional sensory information to be sent to the CNS. As the brain processes this information it can make better decisions when responding to the unstable foam surface.

1) Stop watch
   -necessary for timing the subjects during the 6, twenty second trials

2) An assistant to act as a spotter
-the spotter is necessary to assist the subject should they become unstable and begin to fall. The spotter's attention is especially important during the foam surface.
3) BESS Testing Protocol
-these instructions should be read to the subject during administration of the BESS
4) BESS Score Card (See end of document)
5) Before administering the BESS, the following materials should be present:
-foam pad
-stop watch
-spotter
-BESS Testing Protocol
-BESS Score Card

1) Before testing, instruct the individual to remove shoes and any ankle taping if necessary. Socks may be worn if desired.
2) Read the instructions to the subject as they are written in the BESS Testing Protocol.
3) Record errors on the BESS Score Card as they are described below.

**BESS TESING ADMINISTRATION**

**Scoring the BESS**

Each of the twenty-second trials is scored by counting the errors, or deviations from the proper stance, accumulated by the subject. The examiner will begin counting errors only after the individual has assumed the proper testing position.

*Errors:* An error is credited to the subject when any of the following occur:
_moving the hands off of the iliac crests
_opening the eyes
_step stumble or fall
_abduction or flexion of the hip beyond 30° _
_lifting the forefoot or heel off of the testing surface
_remaining out of the proper testing position for greater than 5 seconds

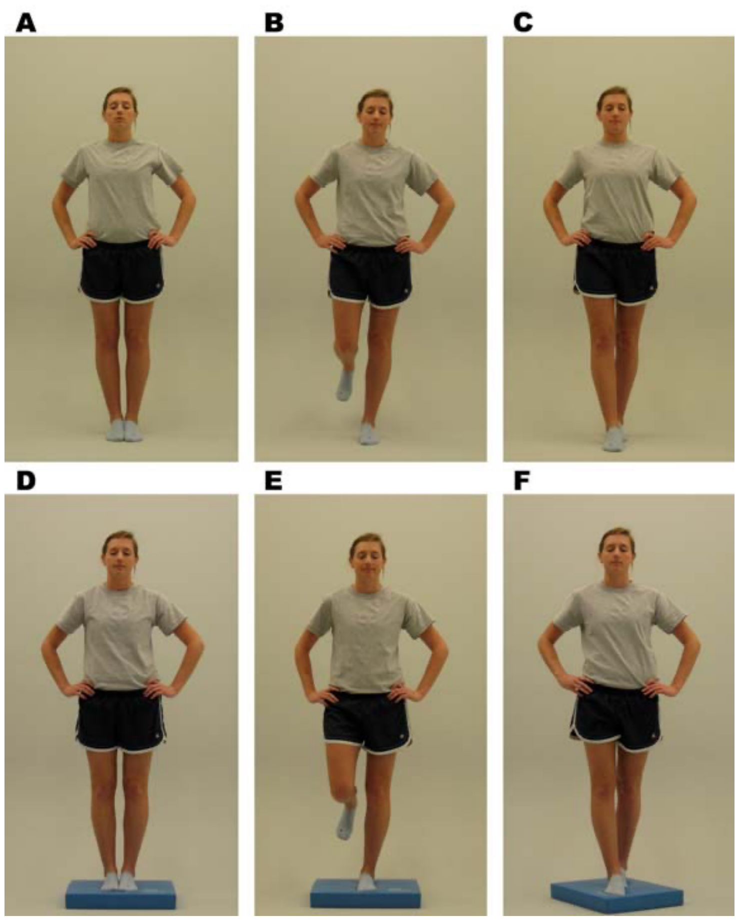
**The maximum total number of errors for any single condition is 10**.

| *Normal Scores for Each Possible Testing Surface* | | |
|---|---|---|
| Double Leg Stance | .009 ± _.12 | .33 ± _.90 |
| Single Leg Stance | 2.45 ± _2.33 | 5.06 ± _2.80 |
| Tandem Stance | .91 ± _1.36 | 3.26 ± _2.62 |
| **Surface Total** | 3.37 ± _3.10 | 8.65 ± _5.13 |
| **BESS Total Score** | 12.03 ± _7.34 | |

-if a subject commits multiple errors simultaneously, only one error is recorded. For example, if an individual steps or stumbles, opens their eyes, and removes their

hands from their hips simultaneously, then they are credited with only **one error**.
-subjects that are unable to maintain the testing procedure for a minimum of **five seconds** are assigned the highest possible score, ten, for that testing condition.
*A&D:* ***Double leg stance***: Standing on a firm surface with feet side by side (touching), hands on the hips and eyes closed

*B&E:* ***Single leg stance***: Standing on a firm surface on the non-dominant foot (defined below), the hip is flexed to approximately 30° and knee flexed to approximately 45°. Hands are on the hips and eyes closed.
**Non-Dominant Leg*: The non-dominant leg is defined as the opposite leg of the preferred kicking leg
*C&F:* ***Tandem Stance***: Standing heel to toe on a firm surface with the non- dominate foot (defined above) in the back. Heel of the dominant foot should be touching the toe of the non-dominant foot. Hands are on the hips and their eyes are closed.



**Script for the BESS Testing Protocol** **Direction to the subject:** *I am now going to test your balance.*

*Please take your shoes off, roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable).*
*This test will consist of 6 - twenty second tests with three different stances on two different surfaces. I will describe the stances as we go along.*

**DOUBLE LEG STANCE:**
**Direction to the subject:** *The first stance is standing with your feet together like this*[administrator demonstrates two-legged stance]

*You will be standing with your hands on your hips with your eyes closed. You should try to maintain stability in that position for entire 20 seconds. I will be counting the number of times you move out of this position. For example: if you take your hands off your hips, open your eyes, take a step, lift your toes or your heels. If you do move out of the testing stance, simply open your eyes, regain your balance, get back into the testing position as quickly as possible, and close your eyes again.*

*There will be a person positioned by you to help you get into the testing stance and to help if you lose your balance.*

**Direction to the spotter:** *You are to assist the subject if they fall during the test and to help them get back into the position.*
**Direction to the subject:** *Put your feet together, put your hands on your hips and when you close your eyes the testing time will begin* [Start timer when subject closes their eyes]
SINGLE LEG STANCE:
**Direction to subject:** *If you were to kick a ball, which foot would you use?* [This will be the **dominant** foot] *Now stand on your **non-dominant** foot.*

[Before continuing the test assess the position of the dominant leg as such: the dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion]

*Again, you should try to maintain stability for 20 seconds with your eyes closed. I will be counting the number of times you move out of this position.*

*Place your hands on your hips. When you close your eyes the testing time will begin.*

[Start timer when subject closes their eyes]

**Direction to the spotter:** *You are to assist the subject if they fall during the test and to help them get back into the position.*

**TANDEM STANCE:**
**Directions to the subject:** *Now stand heel-to-toe with your* **non-dominant** *foot in back.*

*Your weight should be evenly distributed across both feet.*

*Again, you should try to maintain stability for 20 seconds with your eyes closed. I will be counting the number of times you move out of this position.*

*Place your hands on your hips. When you close your eyes the testing time will begin.*

[Start timer when subject closes their eyes]

**Direction to the spotter:** *You are to assist the subject if they fall during the test and to help them get back into the position.*

APPENDIX B

MAX JUMP RAW SCORES

***Table 10. Max Jump scores (inches) for Pre, Post and Retention times.*** **All variables represented as Mean (SD).**

| **Group** | **Pre-Test Max Jump (inches)** | **Post-Test Max Jump (inches)** | **Retention Max Jump (inches)** |
|---|---|---|---|
| *Control* | 18.11 (5.32) | 18.76 (5.89) | 18.71 (5.46) |
| *OPTIMAL* | 19.48 (4.72) | 19.95 (4.73) | 19.93 (4.67) |

***Table 11. Max Jump score differences (inches) between Pre/Post and Post/Retention. All variables represented as Mean (SD).***

| **Group** | **Pre to Post Difference Max Jump** | **Pre to Retention Difference Max Jump** |
|---|---|---|
| *Control* | 0.65 (1.03) | 0.60 (1.22) |
| *OPTIMAL* | 0.46 (0.71) | 0.45 (1.77) |

APPENDIX C

RAW COP AND BESS SCORES

***BESS Pre-Test***

| **Group** | **BESS 1** | **BESS 2** | **BESS 3** | **BESS 4** | **BESS 5** | **BESS 6** |
|---|---|---|---|---|---|---|
| *Control* | 0 (0) | 3.37 (2.74) | 0.62 (1.32) | 0.03 (0.18) | 7.58 (2.13) | 2.21 (2.30) |
| *OPTIMAL* | 0 (0) | 4.45 (2.78) | 0.45 (0.69) | 0.10 (0.41) | 7.96 (1.97) | 1.93 (2.54) |

***BESS Post-Test***

| **Group** | **BESS 1** | **BESS 2** | **BESS 3** | **BESS 4** | **BESS 5** | **BESS 6** |
|---|---|---|---|---|---|---|
| *Control* | 0.06 (0.37) | 3.93 (3.16) | 0.47 (0.89) | 0 (0) | 7.6 (2.50) | 2.03 (2.37) |
| *OPTIMAL* | 0 (0) | 3.77 (2.93) | 0.52 (0.85) | 0.07 (0.38) | 8.51 (1.91) | 1.85 (2.07) |

***BESS Retention***

| **Group** | **BESS 1** | **BESS 2** | **BESS 3** | **BESS 4** | **BESS 5** | **BESS 6** |
|---|---|---|---|---|---|---|
| *Control* | 0 (0) | 4 (2.89) | 0.51 (1.12) | 0.03 (0.18) | 7.65 (2.37) | 2.03 (1.93) |
| *OPTIMAL* | 0 (0) | 4.28 (2.52) | 0.43 (0.88) | 0 (0) | 8.70 (1.56) | 1.81 (2.13) |

***CoP Pre-Test***

| Group | CoP 1 | CoP 2 | CoP 3 | CoP 4 | CoP 5 | CoP 6 |
|---|---|---|---|---|---|---|
| *Control* | 43.56 (13.42) | 201.27 (81.88) | 133.23 (59.44) | 149.53 (37.61) | 302.63 (79.47) | 250.23 (110.25) |
| *OPTIMAL* | 39.86 (11.92) | 210.8 (81.18) | 119 (53.70) | 128.93 (28.90) | 301.06 (75.97) | 243.36 (127.75) |

***CoP Post-Test***

| Group | CoP 1 | CoP 2 | CoP 3 | CoP 4 | CoP 5 | CoP 6 |
|---|---|---|---|---|---|---|
| *Control* | 48.9 (16.67) | 201.5 (77.93) | 141.16 (67.28) | 136.37 (36.62) | 290.06 (70.15) | 236.53 (76.15) |
| *OPTIMAL* | 43.14 (14.88) | 182.03 (61.28) | 125.16 (52.87) | 122.13 (34.10) | 282.03 (55.73) | 229.46 (86.67) |

***CoP Retention***

| Group | CoP 1 | CoP 2 | CoP 3 | CoP 4 | CoP 5 | CoP 6 |
|---|---|---|---|---|---|---|
| *Control* | 46.63 (13.90) | 198.1 (76.27) | 135.5 (69.75) | 130.5 (39.62) | 286.2 (83.23) | 215.2 (73.89) |
| *OPTIMAL* | 44.3 (11.99) | 185.46 (70.04) | 113.67 (45.67) | 118.53 (35.71) | 289.73 (72.31) | 218.13 (87.45) |